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EARTHQUAKE ENGINEERING SUPPORT
PHASE 5

Final Technical Report

by

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SUMMARY

This report summarizes the findings of an experimental study supported by the U.S. Army Centrifuge Research Center and Engineer Earthquake Engineering Research Program (EQEN) into the behavior of saturated sands under high initial effective confining stresses subjected to strong ground shaking. The research was conducted using the Army Centrifuge at the U.S. Army Engineering Research and Development Center (ERDC), located in Vicksburg, MS. A large dataset of the response of saturated sand to dynamic shaking under 'level ground' conditions has been compiled and a series of verification models have been conducted. Several techniques were used to investigate the response of deep soil sites (in excess of 70m) including surcharges, lowered water table and higher acceleration (gravities). The most effective approach was to test specimens at higher gravity, as the interpretation of data from specimens tested using a heavy surcharge on the ground surface, or a deep water table has proved difficult. Many deep samples showed a limit to the excess pore pressure generated during shaking at a level much less than 100% of the initial vertical effective stress. A range of explanations has been proposed, including container effects, saturation, compression of the soil, redistribution of pore pressure and dynamic response of the surcharge. The verification tests eliminated container effects, and parallel research by others has shown that there are several reasons for pore pressure generation at depth to be limited. However, as postulated in earlier stages of this research, there is no absolute limit: in a fully saturated specimen of broadly uniform permeability, liquefaction was observed within a few cycles of strong shaking throughout (to an equivalent field depth of around 65m). A second key finding indicates that dense layers overlying loose layers may still be readily liquefied as a consequence of the high excess pore pressures generated below. These findings are highly significant for designers.

LIST OF KEYWORDS

liquefaction
centrifuge
earthquake
model
experiment
sand
dam safety

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1.0   BACKGROUND

This research contract addressed a further phase in the completion of an experimental and analytical research programme in support of the Earthquake Engineering Research Program under the direction of the USAE ERDC (formerly the Waterways Experiment Station), Vicksburg, Mississippi. The phase was entitled Earthquake Induced Liquefaction in Deep Sand Deposits. This study was a continuation of earlier research under Contract Nos. N68171-98-C-9014, N68171-97-M-5710, N68171-97-C-9012, N68171-99-C-9021 and N68171-00-M-5505. The research involved further interpretation of the early experimental data, design of verification experiments, interpretation and analysis of new experimental data and preparation of technical papers for publication. The work was completed in September 2001.

2.0   INTRODUCTION

The current state-of-practice for the evaluation of liquefaction potential and for remediation design and analysis depends on empirical correlations of in-situ measurements of strength versus field experience of liquefaction at shallow depth and laboratory data of the behavior of confined elements under cyclic loading. (Liquefaction is defined here to mean the development of pore pressure equal to 100% of the initial vertical effective stress.) This approach is known as the "simplified procedure". Opinions vary as to the maximum depth in the field at which liquefaction has been observed, but there is no established field evidence from historic earthquakes of liquefaction at depths greater than a few tens of meters. The NCEER Workshop in 1996 on the Evaluation of Liquefaction Resistance of Soils noted that the simplified procedure was developed from evaluations of field observations and field and laboratory test data, Youd and Idriss (1997). The report notes, "These data were collected mostly from sites ... at shallow depths (less than 15m). The original procedure was verified for and is applicable only to these site conditions".

Hence, in design practice the assessment of liquefaction under high initial effective confining stress, such as might relate to the foundations of large earth dams, is based on the extrapolation of observed behavior and correlations at shallow depths. In practice, the behavior of saturated soil under these conditions is not well understood. Based on the results of laboratory tests, researchers have postulated that there is a reduction in the liquefaction resistance of such soil compared to shallow depths. This reduction is accounted for in standard approaches by a ratio known as K_σ, a "correction factor" developed by Seed (1983) in the simplified procedure. This strength ratio is postulated to reduce with increasing initial effective confining stress, which has a large impact potentially on the extent and method (hence cost) of remedial construction required to assure adequate seismic performance of large dams. For example, it may reduce the cyclic shear stress ratio predicted to cause liquefaction in a soil layer under a typical large dam (of the order of 30m high) to about 50% of its value in the absence of the dam. The predicted deformations and resistance and the remedial strength required are a direct function of the reduced shear strength. The K_σ strength reduction therefore

has a strong influence on the decision to remediate a large dam and on the costs of that remediation.

The factor K_σ quantifies the curvature in the cyclic shear strength envelope (cyclic shear stress required to cause liquefaction versus confining stress) for a soil as observed in laboratory tests on discrete specimens. Although some curvature may be expected, such large reductions in cyclic shear strength ratios are counter-intuitive. It is generally accepted that increased confining stress should broadly improve the capacity of a soil to resist applied loads, not reduce it. Clearly the volume of soil that requires to be treated and the difficulty and expense of that treatment are highly dependent on an accurate assessment of the potential for and consequences of liquefaction.

There is therefore strong motivation for owners of large dams to investigate the behavior of saturated sands subject to strong ground shaking under high initial effective confining stresses. In the absence of field data, the use of a centrifuge was considered to be the only practical option to realistically represent a deep soil deposit subjected to earthquake shaking. The experiments reported herein relate exclusively to level ground initial stress conditions in a single layer (loose) or two-layer (dense over loose) deposit of clean, fine sand.

Liquefaction of a level sand bed has previously been the subject of research by many others. Experiments using Nevada sand were conducted at many centrifuge centers under the VELACS project, Arulanandan and Scott (1994). The objective of the ERDC study is to investigate the onset of liquefaction under much higher initial effective overburden stresses than used in the VELACS experiments. Nevada sand, which was used in the VELACS research and has been extensively studied in the laboratory, was adopted for the series of experiments under the ERDC centrifuge test program.

3.0   THE ERDC CENTRIFUGE FACILITY

The design specification for the ERDC centrifuge followed a review of the Army's research needs and a study of the available academic facilities, Ledbetter (1991). Many of the field problems with which the U.S. Army Corps of Engineers is concerned are physically large, such as earth dams, locks and river control structures, environmental problems and military research. It was determined that a new facility with a high payload capacity and high g capability was required to meet future Army needs. A large beam centrifuge was commissioned, Figure 1, termed the Acutronic 684, based on the French designed Acutronic 661, 665 and 680 series of geotechnical centrifuges, Ledbetter et al. (1994a). The capacity of the ERDC centrifuge is a payload of 8 tonnes at up to 143 g, reducing to 2 tonnes at 350 g, with a platform area of 1.3m square. This high capacity enables field problems of the order of up to 300m in breadth, 300m in depth, and 1000m in length to be simulated under a wide variety of loading conditions. The facility is equipped with a large range of equipment and appurtenances.
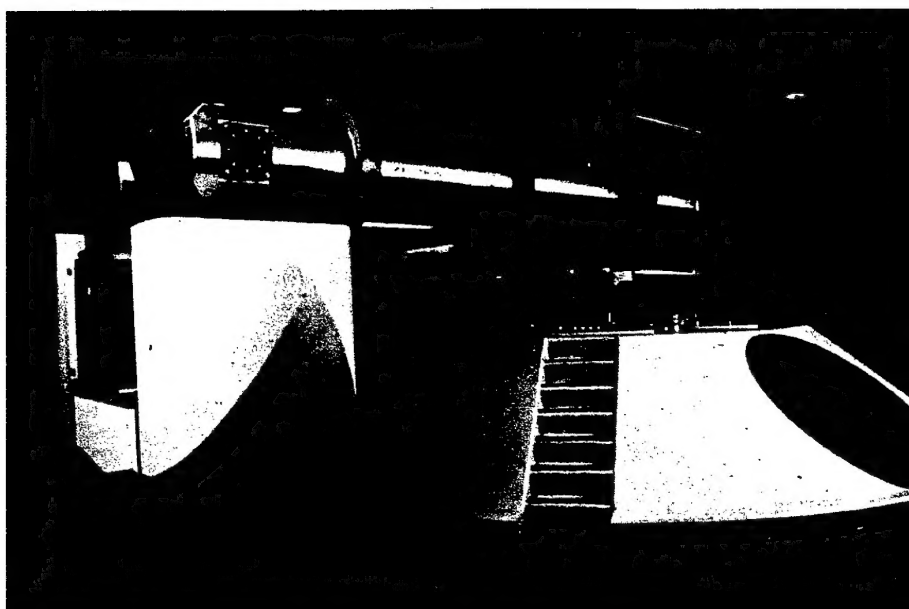
Figure 1. The WES centrifuge

The research approach for this high confining stress liquefaction study uses the large capacity of the WES centrifuge to investigate the generation of excess pore pressure and liquefaction under conditions that much more closely resemble those at depth in the field, Ledbetter et al. (1999). To do this required the design and construction of a large dynamic actuator. The history, design and characteristics of the actuator and specimen container have been discussed in a previous Technical Report, Steedman (2000) and are not repeated here.

4.0 RESEARCH PROGRAM

Table 1 summarises the experiments conducted during 1998 and 2001. The models are grouped in series, where each series corresponds to a different target range of vertical effective overburden stress in the loose layer.

Model series	Models in series	Effective overburden stress near bottom	Equivalent field depth (approx)	Depth of specimen	Notes (all specimens constructed from Nevada Sand, tested at 50g unless specified)
2	a, b, c, d, e, f	110 KPa (1 tsf)	15 m	300 mm	Fully submerged
3	a, b, c, d, e, f	210 KPa (2 tsf)	26 m	525 mm	Fully submerged (3f at 100g)
4	a, b, c, d	320 – 540 KPa (3 – 5 tsf)	26 – 40 m	525 mm	Lowered phreatic surface or surcharge (weights)
	e, f, g, h, i, j	420 – 1040 KPa (3.9 – 9.7 tsf)	30 – 60 m	525 mm	Surcharge (weights) and fully submerged, tested up to 125g
	k	200 – 510 KPa (1.9 – 4.8 tsf)	25 – 39 m	525 mm	No surcharge, fully submerged, tested up to 125g
5	a, b, c, d, e	750 – 1070 Kpa (7 – 10 tsf)	54 – 63 m	525 mm	Surcharge (weights), fully submerged
	f, g	740 KPa (6.9 tsf)	41 m	525 mm	Surcharge (weights), fully submerged (5g reused Model 3e)
	h	610 KPa (5.7 tsf)	41 m	525 mm	No surcharge, fully submerged, tested up to 125g
	i	730 KPa (6.8 tsf)	41 m	460 mm	No surcharge, lowered phreatic surface, tested at 125g

Table 1. Outline summary of centrifuge model test program

Model Code	Overall depth (mm)	Relative Density (D_r)*	σ_v' near base of specimen (tsf)	OCR	Number of earthquakes	Comments (all models constructed from Nevada Sand and tested at 50g unless specified)
2a	300	44% loose, 83% dense	1	1	3	Fully submerged
2b	300	50% loose, 75% dense	1	1	2	Fully submerged
2c	300	49% loose, 74% dense	1	1	5	Fully submerged
2d	300	50% loose, 75% dense	1	1	4	Fully submerged
2e	300	49% loose, 73% dense	1	2.5	4	Fully submerged
2f	300	50% loose, 75% dense	1	2.5	4	Fully submerged
3a	525	34% loose, 73% dense	2	1	2	Fully submerged
3b	525	49% loose, 77% dense	2	1	3	Fully submerged
3c	525	49% loose, 79% dense	2	1	3	Fully submerged
3d	525	54% loose, 80% dense	2	2.5	4	Fully submerged
3e	525	50% loose, 75% dense	2	1	1	Fully submerged
3f	262	50% loose, 75% dense	2	1	1	182 mm dense layer overlying 80 mm loose layer, fully submerged, no surcharge, 100g
4a	525	49% loose, 80% dense	3	1	4	Saturated to top of loose layer only.
4b	525	56% loose, 74% dense	3	2.5	4	Saturated to top of loose layer only.
4c	525	50% loose, 75% dense	4.7	1	4	Fully submerged, surcharge (weights)
4d	525	50% loose, 68% dense	4.7	2.5	4	Fully submerged, surcharge (weights)
4e	525	47% uniform	3.9 – 7.8	1	2,1,1	Fully submerged, surcharge (weights), Shaking at 50, 80, 100g
4f	525	55% uniform	3.9 – 9.7	1	1,1,2,1	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g
4g	525	50% uniform	3.9 – 9.7	1	1,1,1,2	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g
4h	525	50% uniform	3.9 – 9.7	1	1,1,1,1	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g
4i	525	50% uniform	3.9 – 9.7	1	1,1,1,1	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g
4j	525	50% uniform	3.9 – 9.7	1	1,1,1,2	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g.
4k	525	50% uniform	1.9 – 4.8	1	1,1,1,2	Fully submerged, no surcharge, Shaking at 50, 80, 100, 125g.
4l	525	Densities uncertain	4.8	1	1	Fully submerged, surcharge (weights)
5a	525	51% loose, 72% dense	7.4	1	4	Fully submerged, surcharge (weights)
5b	525	49% loose, 76% dense	7.4	2.5	4	Fully submerged, surcharge (weights)
5c	525	52% loose, 75% dense	9.2	1	3	Fully submerged, surcharge (weights)
5d	525	57% loose, 80% dense	9.2	1	1	Fully submerged, surcharge (weights)
5e	525	50% uniform	8.4	1	7	Fully submerged, surcharge (weights)
5f	525	50% loose, 75% dense	6.9	1	1	Fully submerged, surcharge (weights)
5g	525	50% loose, 75% dense	6.9	1	1	Fully submerged, surcharge (same model as 3e with surcharge added)
5h	525	49% loose, 74% dense	5.7	1	1	Fully submerged, no surcharge, 125g
5i	460	50% loose, 75% dense	6.8	1	1	396 mm dense layer, saturated to depth of 250mm only, overlying 64 mm loose layer, no surcharge, 125g

*Relative density of the portion of the model termed 'loose', generally refers to a 160 mm thick layer placed at the bottom of the model. For the 'model of the model' experiments, this loose layer was reduced in depth. Relative density of the portion of the model termed 'dense', refers to that portion of the model above the 'loose' layer (ranged in thickness from 140 to 365 mm). Model 4l was understood to have been built to the standard specification, i.e. 75% dense over 50% loose.

Table 2. Summary description of centrifuge model test program

Generally, specimens were up to 525mm deep with the bottom 160mm placed at around 50% Relative Density (RD) and the upper portion at around 75% RD. The 'early' models were shaken at 50g; later models were shaken at up to 125g. During the verification phase modelling of models was carried out at 100g and 125g. Some models were overconsolidated by a factor of 2.5 prior to shaking (achieved by running the centrifuge up to 125g and then dropping back to 50g). The size of the dataset and number of repetitions provided the opportunity to characterise the data on the basis of the quality of the output. This is seen in Appendix A, where the summary data for each transducer and each earthquake analysed is presented. A quality rating of low/medium/high and * was assigned to each time history based on the consistency and reliability of the data and the quality of the experiment itself. For example, higher 'quality ratings' would be assigned to transducers which showed internal consistency in terms of static pore pressures, physical location in the model, response during shaking etc.

The Nevada sand used in the models was characterized by standard laboratory tests to determine parameters such as dry density and gradation. Table 3 presents key material parameters for this sand.

Specific gravity	2.64
Maximum void ratio	0.757 (density 93.8 pcf)
Minimum void ratio	0.516 (density 108.7 pcf)
D_{50}	0.18 mm (approx)
D_{10}	0.11 mm (approx)

Table 3. Nevada Sand (parameters as measured)

The pore fluid comprised a mixture of glycerine and water, 80% by weight for experiments conducted at 50g. Measurements of the viscosity of glycerine-water mixes at a range of temperatures and proportions show that the viscosity is sensitive to both parameters.

The density of a glycerine-water mix was calculated from:

$$\rho_m = \rho_g(m_g + m_w)/(m_g + \rho_g\, m_w)$$

where ρ_m is the density of the mix, ρ_g is the density of glycerine, m_g is the mass of glycerine, and m_w is the mass of water. Table 4. summarizes the properties of the glycerine-water solution used as the pore fluid.

Density	1200 kg/m^3
Viscosity	50 cs
Specific Gravity	1.26
Composition	80% glycerine-water mix (by weight)

Table 4. Parameters for pore fluid (as measured)

The models were poured dry from a hopper and saturated under vacuum, or slowly under gravity. Instrumentation was placed in the model as it was being constructed.

The typical arrangement of the model specimens for the different test series is shown in Figure 2. Instrumentation was positioned through the depth of the models, and comprised pore pressure transducers and accelerometers. The location of the instrumentation for Model 5b is shown in Figure 3.
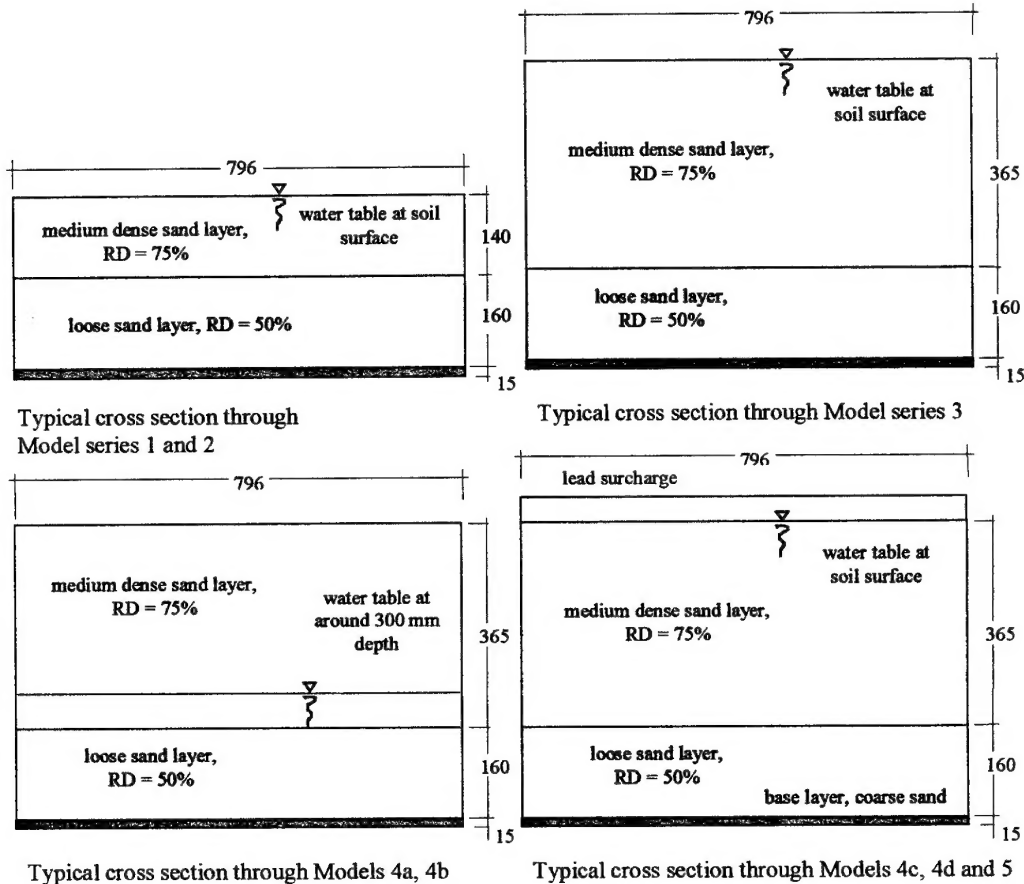

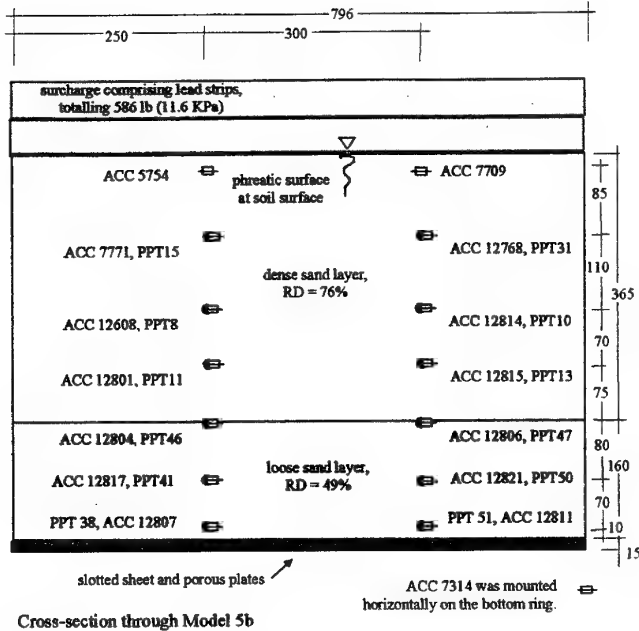Figure 2. Cross sections through the different model configurations

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Cross-section through Model 5b

Figure 3. Instrumentation for Model 5b

5.0   RESULTS

Earlier reports, Steedman (1999), (2000) have presented analysis of the data using a range of approaches. In this report, the data from the verification models is summarized alongside the earlier experimental results, and in the same format.

Appendix A presents the dataset of limiting excess pore pressures, by model and by transducer. Comments are added concerning the quality of each record, and the experiment in general.

From this set a number of time histories were selected as of particularly high quality for possible future interpretation. This selection was made in part based on the internal consistency of the experimental results, and in part using subjective judgment based on past experience. These data are presented in Figures 4a and 4b, and 5a and 5b, below. In each case, the model reference number and earthquake is given, which can be checked against the commentary in Appendix A. Figures 4a and 5a present the pore pressure records; Figures 4b and 5b present the (matching) base input acceleration time history from the same model test.

A summary of selected data and recommendations for future centrifuge testing of level ground conditions under high effective confining stress has been prepared, Sharp and Steedman (2002).
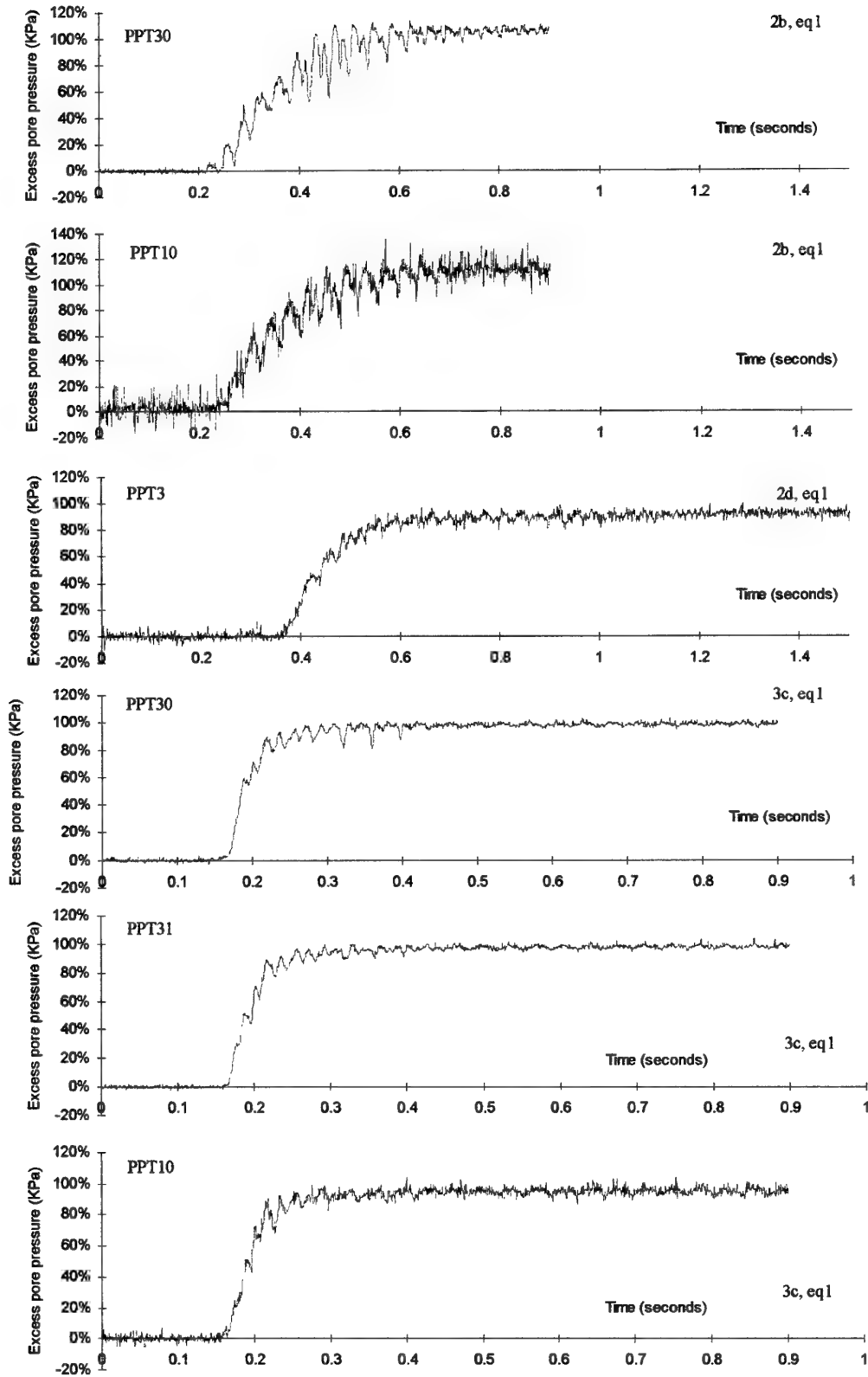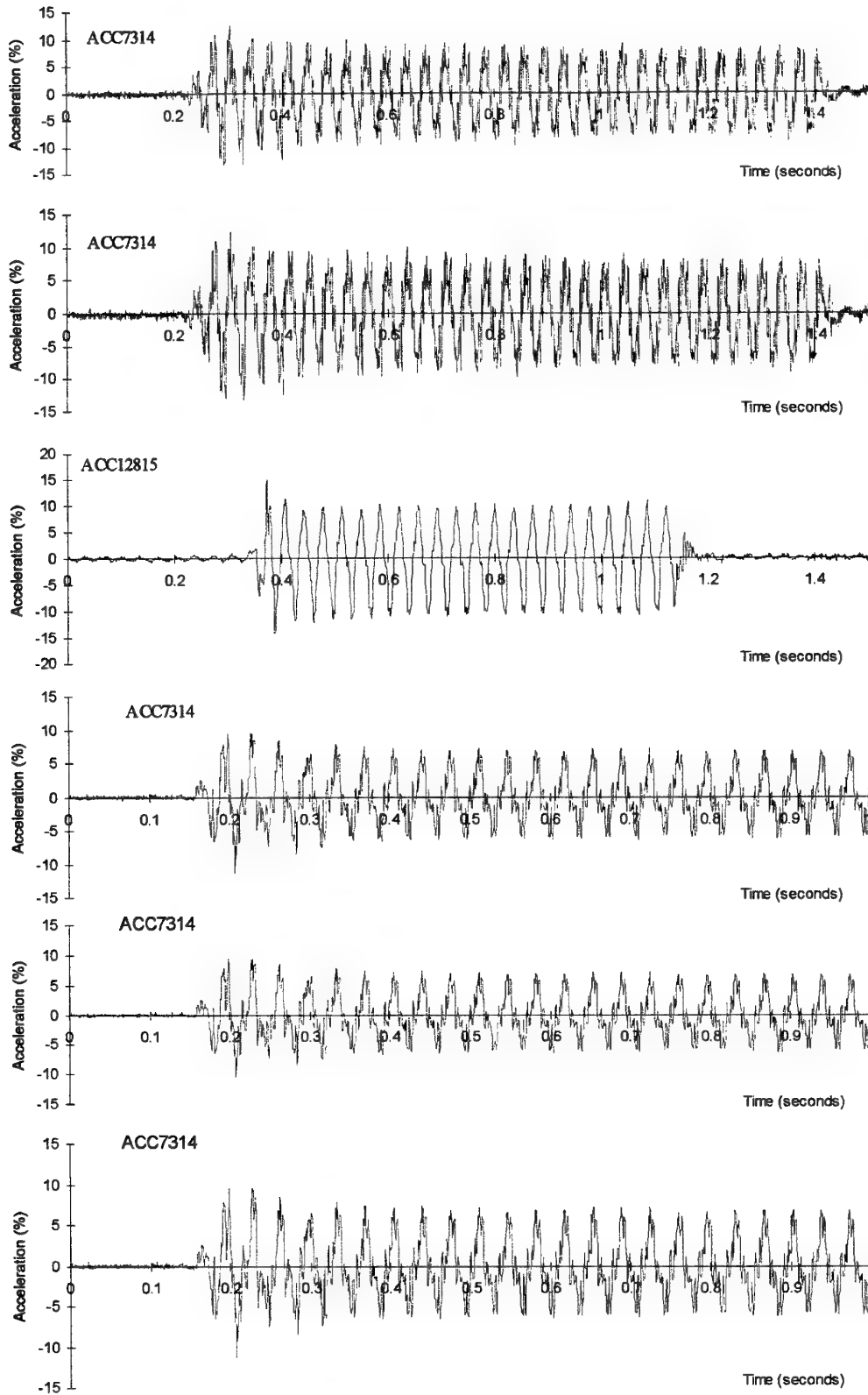
Figure 4a. Selected pore pressure time histories (I)

Figure 4b. Matching acceleration (base input) time histories (I)
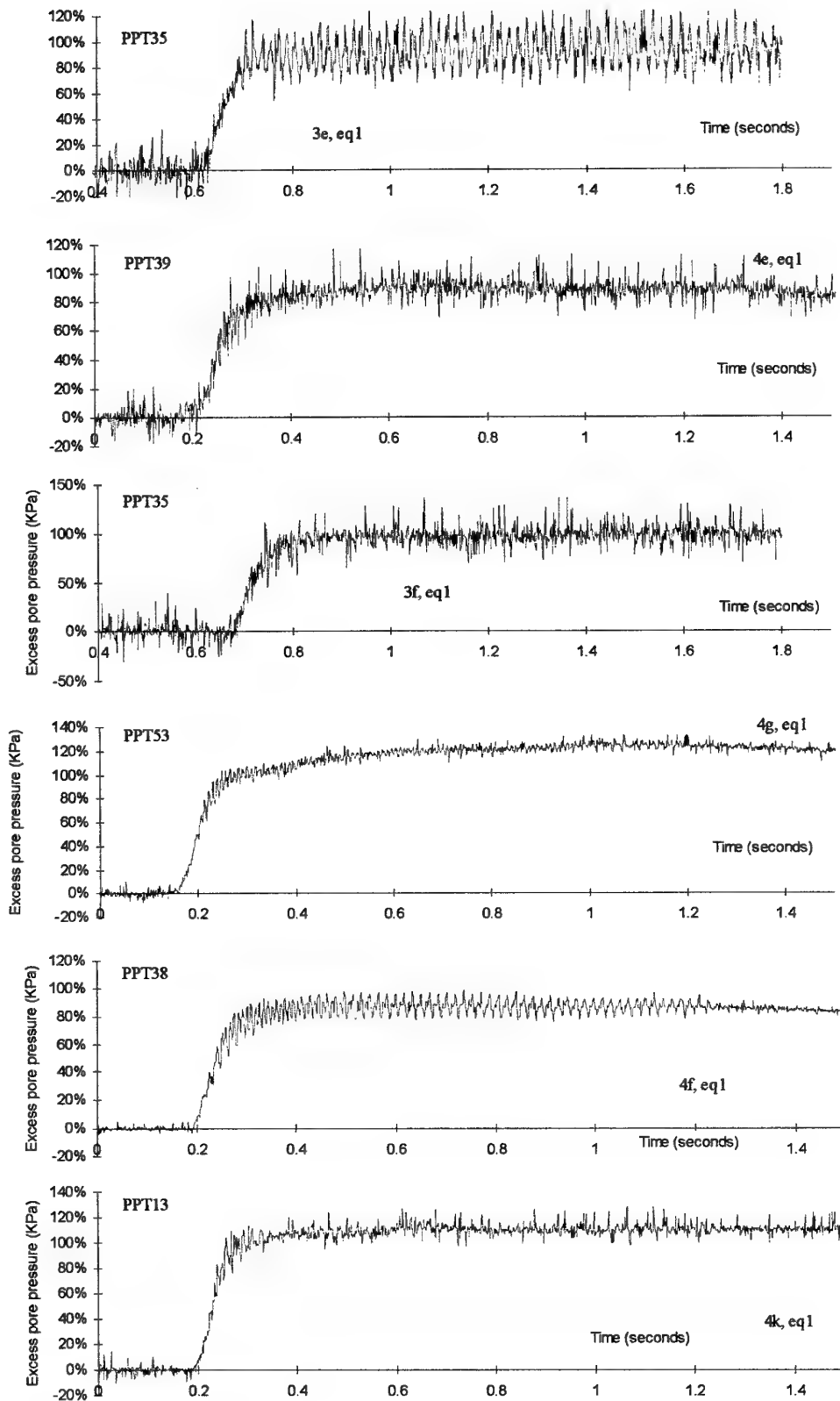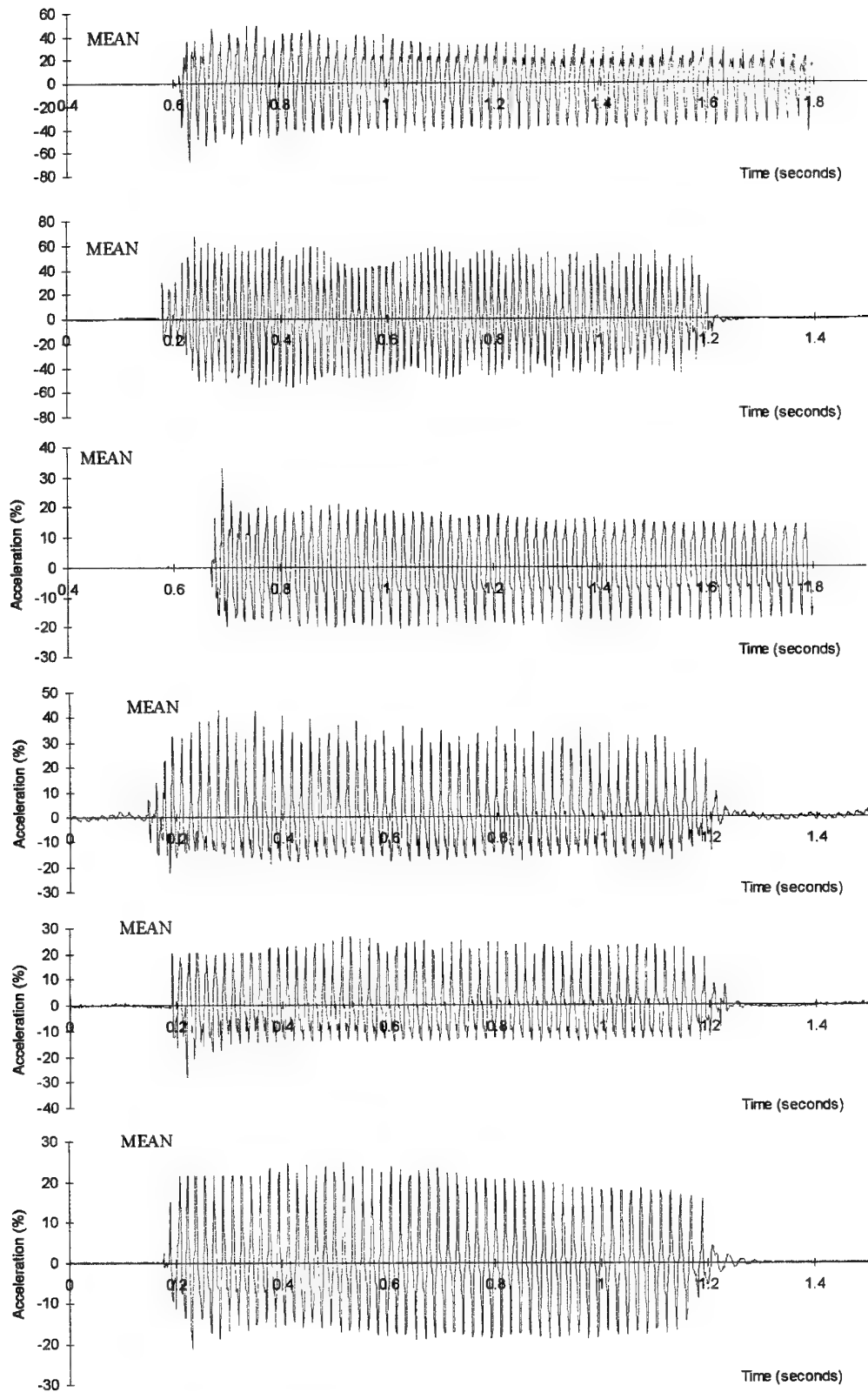
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Figure 5a. Selected pore pressure time histories (II)

Figure 5b. Matching acceleration (base input) time histories (II)

6.0   DETERMINATION OF SHEAR STRESS-STRAIN HISTORIES

All of the experiments undertaken in this study addressed level ground conditions, with no initial static shear stress. The only shear stress and subsequent shear strain was that imposed by the loading. Level ground liquefaction is therefore a special case of the cyclic mobility phenomenon that occurs when the static shear stress is less than the shear strength of the liquefied soil. Level ground liquefaction failures are caused by the upward flow of water that occurs when seismically induced excess pore pressures dissipate. Depending on the length of time required to reach hydraulic equilibrium, level ground liquefaction failure may occur well after ground shaking has ceased and this was seen in a number of the experiments. References in Appendix A to transducers 'still climbing at the end of shaking' are evidence of pore pressure redistribution affecting the pore pressure generation caused by shaking.

A critical aspect in the assessment of these model experiments was to compute the stress strain time histories for comparison with laboratory element and field experience. This was done in collaboration with researchers at WES and RPI.

The method adopted to compute the stress and strain time histories was known as System Identification or SI. The method is described in a paper by Zeghal et. al. (1995), where the authors proposed that accelerometer and pore pressure time histories could offer a direct and effective means of evaluating seismic soil properties, in particular, a second order accurate estimation of shear stress and shear strain. This SI technique was utilized for analysis of the earthquake data.

Stress strain figures are shown here for Models 4k (Figure 6) and 5b (Figure 7), windowed during similar stages of shaking, Steedman and Sharp (2001).

The left column of plots are the traditional stress-strain loops computed for the early time data, as the excess pore pressures are developing strongly. This may be seen by comparison with the time history of vertical effective stress below the stress strain figures. For Model 4k this shows the largest amount of straining near the surface at nearly 1%, decreasing to a strain of 0.6% at a depth of 24 m. The remaining columns of figures show how the stress strain loops are altered by the development of excess pore pressure. In the case of Model 4k, the specimen reaches close to 100% excess pore pressure, and the upper layers become isolated from the straining at the base. In the case of Model 5b, the excess pore pressure is limited and the response of the soil column becomes nearly linear. The marked contrast in response between the two specimens confirm the observation that the stabilization of the excess pore pressure development in the deeper specimens is a genuine phenomenon associated with a stable cycling of applied load at a level significantly below 100% excess pore pressure, and with the soil retaining considerable reserves of strength and stiffness.

One explanation for the limiting level of excess pore pressure may be associated with upward drainage of the excess pore pressures.
Appendix B presents isochrones of stress and strain levels from each experiment, based on this method.
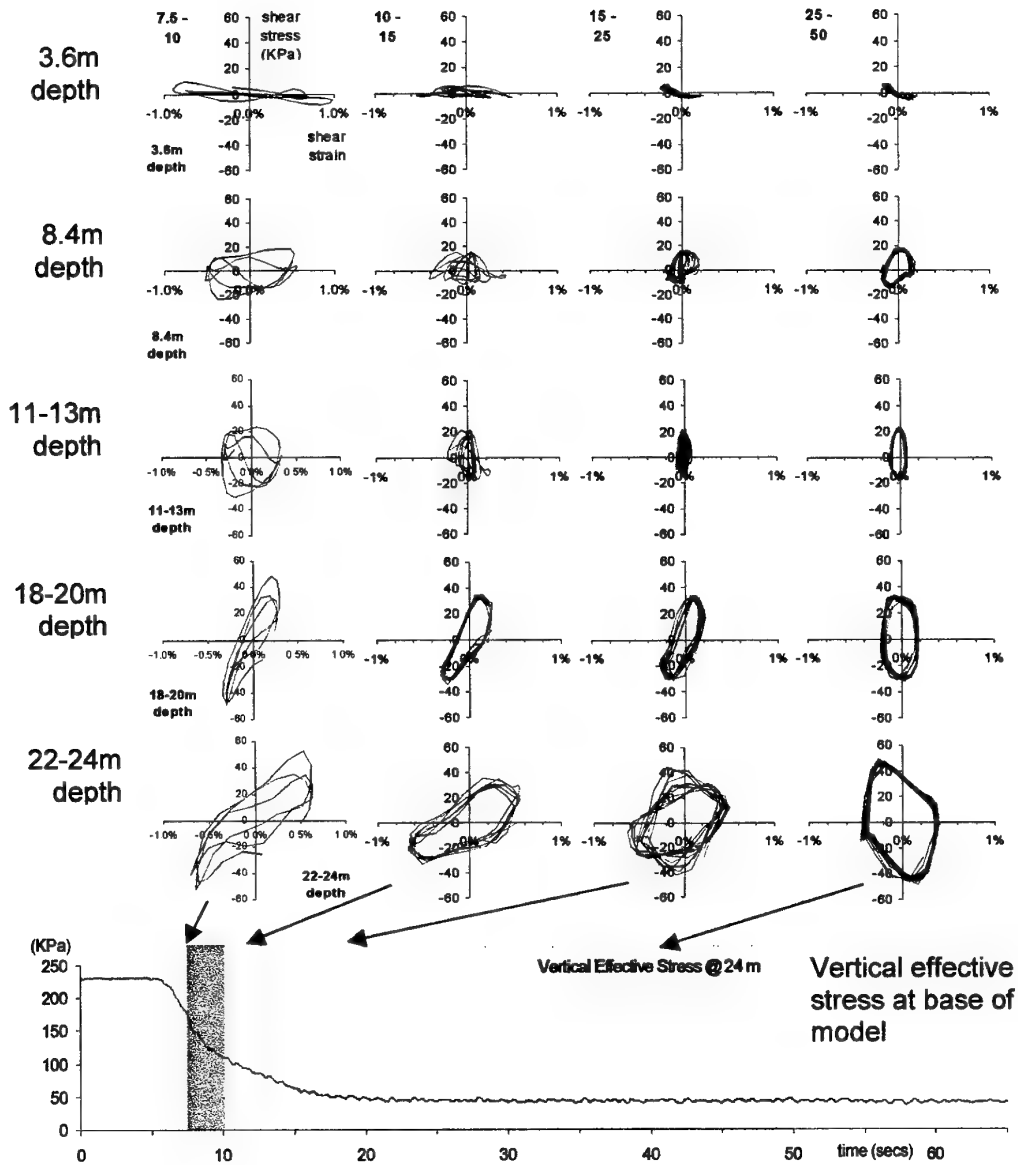
Figure 6. Stress strain time histories, Model 4k
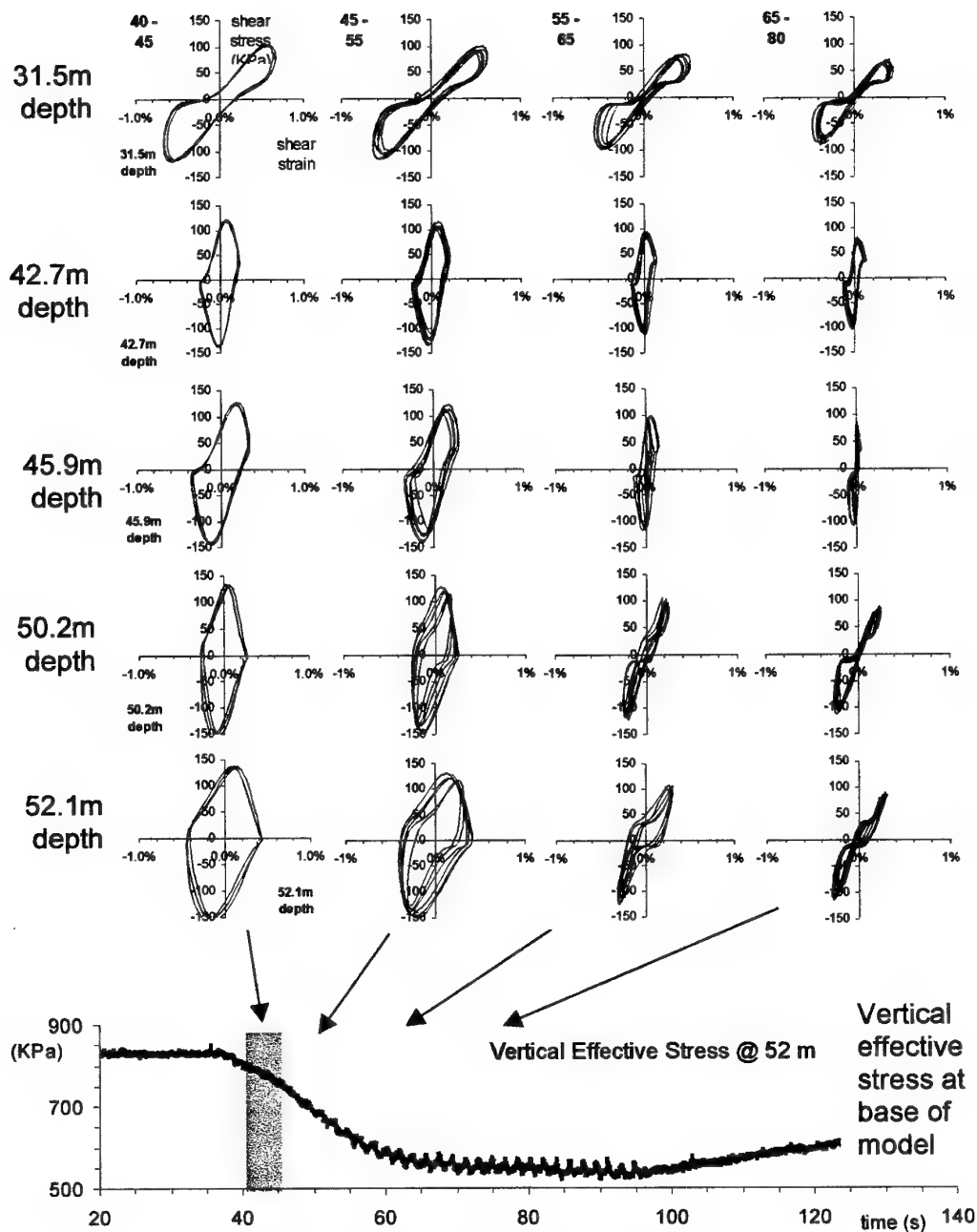
Figure 7. Stress strain time histories, Model 5b

A very large dataset of the behavior of Nevada sand subject to shaking under level ground conditions has been accumulated as a result of this work. Review of the stress-strain data alongside the time histories of excess pore pressure provided considerable additional insight into the explanation of the pore pressure response in many cases. The verification models that were tested during 2000-2001 were successful in validating the performance of the specimen chamber and shaker in many respects. The verification models showed that the use of surcharges may indeed be having an effect on the response of the soil column, although exactly how the surcharge affects the soil column has not yet been conclusively

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determined; many other factors, including soil density, compression and saturation may also be influencing the 'true' response under cyclic loading at high effective confining stress. It is clear that the most effective method of investigating the influence of very high effective confining stress is to use the centrifuge at high g, with or without dry sand surcharging, as for example was achieved with the final experiments in the series, Models 5h and 5i.
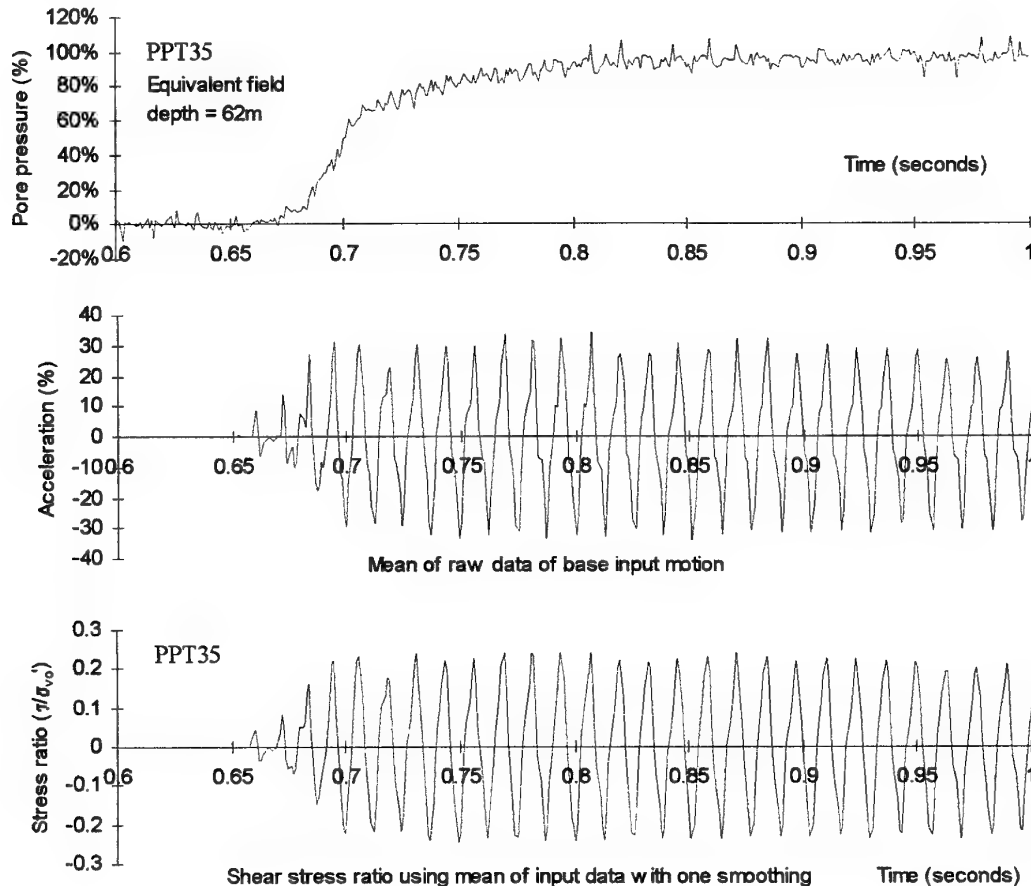
Figure 8. Liquefaction at 62m equivalent depth, Model 5h

Figure 8 presents data from PPT35, Model 5h, which shows 100% excess pore pressure reached after a few cycles of strong shaking in a fully saturated deep specimen without surcharge, at 125g. The shear stress ratio time history shown here was calculated using the simplified method, Steedman (2000) and may be compared to the isochrones of stress ratio calculated using the SI method, Appendix B. Appendix B also shows the long term response after the end of shaking, where consolidation effects and pore pressure redistribution last for a very long period after the end of the earthquake.

7.0 CONCLUSIONS

1. A large data-set of the behavior of loose saturated sands under high initial effective confining stresses and subject to earthquake-like shaking has been collected during an extensive experimental program on the ERDC Centrifuge, Vicksburg MS.

2. Early findings from the centrifuge experiments showed that under high effective confining stress, the potential to generate excess pore pressures was limited, and this may be of considerable importance if verified.

3. Detailed investigation into the early findings has provided a range of explanations for the limiting values, including experimental problems such as specimen saturation, chamber effects or the distorting effects of large surcharges on the soil surface. Of these possible effects, detailed investigation of the response of the chamber effectively eliminated movement, or distortion of the ESB container as an explanation.

4. The effect of surcharging was investigated by comparison with changing g level and using different methods of surcharging, or no surcharges at all. The use of dry sand appeared preferable to lead or steel weights; this method was used in early experiments as well as in later models.

5. In the final experiments, which were carried out at high g without the use of surcharges, liquefaction occurred throughout the entire depth within a few cycles. This experiment confirmed that with sufficient input shaking, large excess pore pressures are generated in a saturated soil column of broadly uniform permeability.

6. A key finding of the study has been to recognise the importance of pore pressure redistribution in deep soil columns, which can cause an 'up-welling' of excess pore pressure from lower layers leading to liquefaction of upper layers some time after shaking has ceased. This is an effect not widely considered in standard design methods.

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APPENDIX A

EARTHQUAKE DATASET

Data of limiting pore pressures, Models and cycles (1998-2001)

EARTHQUAKE DATASET

Data of limiting pore pressures, Models and cycles

Model, Earthquake	Eq	Centrif'g acc'n	Total vertical stress (KPa)	Effective Overburden Pressure (KPa)	Cycles to upper limit	Cycles to 50% excess	Pore pressure Upper limit (%)	Upper value (KPa)	Peak Cyclic stress ratio	Stress ratio 0.65xPeak	Relative Density (%)	Quality low/med/high*	PPT	Comments	Summary details and WES Model Ref
Model 1a, 1	1	50	67.6	34	10.8		59	20.06	0.105	0.068	70	low		31 Uncertain measured depth of transducers, showed double frequency	
Model 1a, 1	1													10 Still climbing at end of datacapture	
Model 1a, 1	1													9 Still climbing at end of datacapture	
Model 1a, 2	2	50	67.6	35	12.4		100	35		0.0511	70	low		31 Ottawa sand. Second eq showed slow rise to final limit	
Model 1a, 2	2													10 Still climbing at end of datacapture	
Model 1a, 2	2													9 Still climbing at end of datacapture	
Model 2a, 1	1	50	70.3	30	2.51		100	30	0.318	0.207	83	low		Near surface acceleration clearly shows liquefaction	20/2/1998, Ref 2
Model 2a, 2	2	50	70.3	30	2.48		100	30	0.25	0.162	83	low	na	Estimated as no ppts functioning	300mm depth
Model 2a, 3	3												na	Probably did not liquefy	44% loose, 83% dense
Model 2b, 1	1	50	221	106	10.719	2.187	110	116.6	0.18	0.117	50	*		10 Clearly over 100%, large cycles affect 50% point	30/4/1998, Ref 5
Model 2b, 1	1	50	223	106	11.529	2.349	105	111.3	0.181	0.118	50	*		30 Double frequency just over 100%, large cycles affect 50% point	300mm depth
Model 2b, 1	1	50	68.9	27	10.611	2.16	110	29.7	0.292	0.19	75	*		31 Clearly over 100%, large cycles affect 50% point	50% loose, 75% dense
Model 2b, 2	2	50	230	111	5.4		104	115.44	0.221	0.143	50	*		10 Very clearly 100%	
Model 2b, 2	2	50	236	115	4.59		98	112.7	0.216	0.141	50	*		30 Rapid rise to 100%	
Model 2b, 2	2	50	76.4	32	5.4		100	32	0.33	0.214	75	*		31 Clear 100%, rapid rise	
Model 2c, 1	1	50	240	98	27.5	13.095	100	98	0.092	0.059	49	high		46 Possibly just reached limit before being cut off	8/6/98, Ref 8
Model 2c, 1	1	50	256	98	27.5	8.343	103	100.94	0.097	0.063	49	high		41 Seems to be very close to limit at the end of the eq	300mm depth
Model 2c, 1	1			99		21.978			0.0899	0.0585	49	high		49 Still climbing when data cut off	49% loose, 74% dense
Model 2c, 1	1	50	69.2	30	8.59	5.238	70	21	0.114	0.074	74	high		37 Reached upper limit early, unlike other depths, high freq rapid rise effects 50% point	
Model 2c, 1	1													42 Erratic response, still climbing at end	
Model 2c, 1	1													39 Erratic response, still climbing at end	
Model 2c, 2	2	50	240	98			96	94.08	0.094	0.061	49	high		46 Very close to limit at end	
Model 2c, 2	2	50	256	98			100	98	0.1	0.065	49	high		41 Very close to limit at end	
Model 2c, 2	2													49 Still climbing at end of shaking	
Model 2c, 2	2	50	70.8	27.6	6.6		75	20.7	0.132	0.085	74	med		37 Reached upper limit early, unlike other depths	
Model 2c, 2	2													42 Erratic response, still climbing at end	
Model 2c, 2	2	50	74.1	30.3	12.8		90	27.27	0.123	0.08	74	med		39 Reached upper limit early, like ppt37	
Model 2c, 3	3													46 Still climbing at end of shaking	
Model 2c, 3	3													41 Still climbing at end of shaking	
Model 2c, 3	3													49 Still climbing at end of shaking	
Model 2c, 3	3	50	70.8	27.6	7.7		70	19.32	0.127	0.083	74	med		37 Reached upper limit early, very noisy response	
Model 2c, 3	3													42 Erratic response, still climbing at end	
Model 2c, 3	3	50	74.1	30.3	15.4		80	24.24	0.069	0.045	74	med		39 Reached upper limit later than ppt37, very noisy	
Model 2c, 4	4													46 Still climbing at end of shaking	
Model 2c, 4	4													41 Still climbing at end of shaking	
Model 2c, 4	4													49 Still climbing at end of shaking	
Model 2c, 4	4	50	70.8	27.6	5.4		70	19.32	0.107	0.07	74	med		37 Reached upper limit early, very noisy response	
Model 2c, 4	4													42 Erratic response, still climbing at end	
Model 2c, 4	4	50	74.1	30.3	36.5		75	22.725	0.1	0.065	74	med		39 Possibly reached limit, very noisy	
Model 2c, 5	5													46 No excess pore pressure	
Model 2c, 5	5													41 No excess pore pressure	

Model	#											Description	Notes
Model 2c, 5	5												49 No excess pore pressure
Model 2c, 5	5												37 No excess pore pressure
Model 2c, 5	5												42 No excess pore pressure
Model 2c, 5	5												39 No excess pore pressure
Model 2d, 1	1	50	188	76	9.45	2.0	106	80.56	0.26	74 *	0.169	3 Good record, dense/loose boundary	12/8/98, Ref 9
Model 2d, 1	1	50	203	88	5	1.5	83	73.04	0.174	49 *	0.113	31 Double frequency at upper limit suggests 100% excess pwp	300mm depth
Model 2d, 1	1	50	317	133	13	2.6	76	101.08	0.187	49 high	0.121	46 point Difficult to identify upper limit, which rises slowly, large cycles affect 50%	50% loose, 75% dense
Model 2d, 1	1	50	124	50	10	2.3	92	46	0.25	74 high	0.162	7 Sank during earthquake, clearly reached limit	
Model 2d, 1	1	50	150	59.4	8.4	1.8	93	55.242	0.242	74 *	0.158	41 Clearly reached limit, dense/loose boundary, large cycles effect 50% point	
Model 2d, 1	1	50	264	112	12.2	2.3	92	103.04	0.193	49 high	0.126	51 Reached limit, cyclic response, large cycles effect 50% point	
Model 2d, 1	1		135			3.3			0.186	49 high	0.121	8 Still climbing slowly at end of shaking, large cycles effect 50% point	
Model 2d, 2	2	50	195	76	9.2		88	66.88	0.338	74 *	0.22	3 Good record, dense/loose boundary	
Model 2d, 2	2	50	204	86.6	4		80	69.28	0.299	49 *	0.194	31 Double frequency at upper limit suggests 100% excess pwp	
Model 2d, 2	2											46 Still climbing at end of earthquake	
Model 2d, 2	2	50	132	49.7	4.3		82	40.754	0.388	74 med	0.252	7 Sank during earthquake, clearly reached limit	
Model 2d, 2	2	50	154	59.4	5.1		90	53.46	0.364	74 *	0.236	41 Clearly reached limit, dense/loose boundary	
Model 2d, 2	2	50	267	112	9.7		90	100.8	0.286	49 high	0.186	51 Reached limit, cyclic response	
Model 2d, 2	2											8 Still climbing slowly at end of shaking	
Model 2d, 3	3	50	196	76	7.7		88	66.88	0.309	74 *	0.201	3 Good record, dense/loose boundary	
Model 2d, 3	3	50	203	87.8	3.6		78	68.484	0.266	49 *	0.173	31 Double frequency at upper limit suggests 100% excess pwp	
Model 2d, 3	3											46 Still climbing at end of earthquake	
Model 2d, 3	3	50	133	50	5		83	41.5	0.353	74 med	0.23	7 Sank during earthquake, clearly reached limit	
Model 2d, 3	3	50	153	59.4	5.9		90	53.46	0.327	74 *	0.213	41 Clearly reached limit, dense/loose boundary	
Model 2d, 3	3											51 Still climbing slowly at end of shaking	
Model 2d, 3	3											8 Still climbing slowly at end of shaking	
Model 2d, 4	4	50	196	76	7.7		84	63.84	0.281	74 *	0.183	3 Good record, dense/loose boundary	
Model 2d, 4	4	50	203	87.8	4.4		78	68.484	0.242	49 *	0.157	31 Double frequency at upper limit suggests 100% excess pwp	
Model 2d, 4	4											46 Still climbing at end of earthquake	
Model 2d, 4	4	50	133	49.7	5		83	41.251	0.321	74 med	0.208	7 Sank during earthquake, clearly reached limit	
Model 2d, 4	4	50	154	59.6	5		88	52.448	0.297	74 *	0.193	41 Clearly reached limit, dense/loose boundary	
Model 2d, 4	4											51 Close, but still climbing slowly at end of shaking	
Model 2d, 4	4											8 Still climbing slowly at end of shaking	
Model 2e, 1	1	125	162	60	13.4	4.2	100	60	0.225	73 med	0.147	52 Kink in pore pressure time history, static readings at 50g unreliable	26/8/98, Ref 10
Model 2e, 1	1	125	270	129	13.2	8.9	72	92.88	0.153	49 high	0.1	47 Static readings at 50g not totally reliable	300mm depth
Model 2e, 1	1	125	373	175	22.4	7.6	76	133	0.144	49 high	0.093	49 Static readings at 50g not totally reliable	49% loose, 73% dense
Model 2e, 1	1	125		38		2.0			0.163	73 med	0.106	Dense layer, rose rapidly at limit, but then started to drop after 0.2 seconds, 43 large cycle affects 50%	
Model 2e, 2	2	125	169	66.8	8		90	60.12	0.211	73 high	0.137	52 Good record	
Model 2e, 2	2	125	269	129	11.2		71	91.59	0.158	49 high	0.103	47 Clear limit, but static readings at 50g not totally reliable	
Model 2e, 2	2	125	381	184	5.3		69	126.96	0.142	49 high	0.092	49 Very rapid rise to limit, but static readings at 50g not totally reliable	
Model 2e, 2	2	125	68.9	42.4	6.9		70	29.68	0.158	73 med	0.103	43 Dense layer, reached some sort of limit but noisy signal	
Model 2e, 3	3	125	169	66.8	9.3		85	56.78	0.218	73 high	0.142	52 Limit, but with cyclic behaviour	
Model 2e, 3	3	125	269	129	14.7		70	90.3	0.163	49 high	0.106	47 Clear limit, but static readings at 50g not totally reliable	
Model 2e, 3	3	125	381	184	3.9		70	128.8	0.146	49 high	0.095	49 Very rapid rise to limit, but static readings at 50g not totally reliable	
Model 2e, 3	3	125	68.9	42.4	3.9		63	26.712	0.163	73 med	0.106	43 Dense layer, reached some sort of limit but noisy signal	
Model 2e, 4	4	125	169	66.8	20.6		83	55.444	0.222	73 high	0.144	52 Limit, but with strong cyclic behaviour	
Model 2e, 4	4	125	269	129	17.9		70	90.3	0.166	49 high	0.108	47 Good record, but static readings at 50g not totally reliable	
Model 2e, 4	4	125	381	184	11.1		68	125.12	0.149	49 high	0.097	49 Very rapid immediate response, then slow rise to limit, as above	
Model 2e, 4	4	125	68.9	42.4	7.1		67	28.408	0.166	73 med	0.108	43 Dense layer, reached some sort of limit but noisy signal	
Model 2f, 1	1	125	172	63	15.4	6.6	99	62.37	0.288	50 *	0.187	31 Excellent, loose/dense interface	22/9/98, Ref 14
Model 2f, 1	1	125	251	101	13.5	7.2	88	88.88	0.237	50 *	0.154	47 Excellent, up to 7.811 for 50%	300mm depth

Model 2f, 1	1	125	320	136	7.34	3.1	85	115.6	0.207	0.134	50 *	46 Excellent	50% loose, 75% dense
Model 2f, 1	1	125	104	32.2	5.21	1.7	115	37.03	0.395	0.257	75 *	38 Excellent	
Model 2f, 1	1	125	102	31.7	5.4	2.4	115	36.455	0.397	0.258	75 *	51 Clear limit, very rapid rise with one or two big cycles, affecting 50%	
Model 2f, 1	1	125	172	62.6	13.5	7.5	93	58.218	0.293	0.191	50 *	15 Good record, loose/dense interface	
Model 2f, 1	1	125	337	138	10.8	3.9	90	124.2	0.213	0.138	50 *	41 Bottom of loose layer, rapid rise to limit, with cycles which may affect 50%	
Model 2f, 2	2	125	177	69	8.6		88	60.72	0.287	0.187	50 *	31 Excellent	
Model 2f, 2	2	125	254	103.5	14		79	81.765	0.248	0.161	50 *	47 Good record	
Model 2f, 2	2	125	320	136	2.2		85	115.6	0.222	0.144	50 *	46 Very rapid rise to limit	
Model 2f, 2	2	125	113	41.4	3.2		80	33.12	0.341	0.222	75 *	38 Clear limit, slightly noisy	
Model 2f, 2	2	125	112	41.9	4.1		82	34.358	0.336	0.218	75 *	51 Clear limit, again noisy	
Model 2f, 2	2	125	177	67.6	20.3		85	57.46	0.294	0.191	50 *	15 Two stage rise to final limit	
Model 2f, 2	2	125	339	140.3	6.8		86	120.658	0.225	0.146	50 *	41 Bottom of model, rapid rise to limit	
Model 2f, 3	3	125	177	69	19.7		92	63.48	0.38	0.247	50 high	31 Reached limit near end of shaking, loose/dense interface	
Model 2f, 3	3	125	254	103.5	34.8		92	95.22	0.328	0.213	50 high	47 Just reached limit near end	
Model 2f, 3	3	125	320	136	4.3		92	125.12	0.293	0.191	50 *	46 Bottom of model, very rapid rise to limit	
Model 2f, 3	3	125	113	41.4	6.2		100	41.4	0.452	0.293	75 *	38 Clear limit, slightly noisy	
Model 2f, 3	3	125	112	41.9	4.9		93	38.967	0.444	0.288	75 *	51 Clear limit, again noisy	
Model 2f, 3	3											15 Still rising at end of shaking	
Model 2f, 3	3	125	339	140	10.3		93	130.2	0.298	0.193	50 *	41 Bottom of model, rapid rise to limit	
Model 2f, 4	4	125	177	69	26.2		83	57.27	0.39	0.254	50 high	31 Reached limit near end of shaking, cyclic response	
Model 2f, 4	4	125	254	103.5	23.5		84	86.94	0.337	0.219	50 high	47 Reached limit near end	
Model 2f, 4	4	125	320	135.7	4.6		86	116.702	0.301	0.196	50 *	46 Bottom of model, very rapid rise to limit	
Model 2f, 4	4	125	113	41.4	7.3		78	32.292	0.463	0.301	75 *	38 Clear limit, slightly noisy	
Model 2f, 4	4	125	112	41.9	4.6		77	32.263	0.455	0.296	75 *	51 Clear limit, again noisy	
Model 2f, 4	4											15 Still rising at end of shaking	
Model 2f, 4	4	125	339	140.3	15.4		82	115.046	0.305	0.199	50 *	41 Bottom of model, slower rise to limit	
Model 3a, 1	1	50	474	181	4.2	1.9	102	184.62	0.314	0.204	34 high	9 spikey acceleration record, but excellent pore pressure data, rapid rise affects 50%	30/3/98, Ref 3
Model 3a, 1	1	50	429	182	3.8	1.8	110	200.2	0.281	0.183	34 high	10 Low static pore pressure value, good dynamic response, rapid rise affects 50%	525mm depth
Model 3a, 2	2	50	477	186	7.9		98	182.28	0.288	0.187	34 high	9 Slow rise contrasts with ppt10	34% loose, 73% dense
Model 3a, 2	2	50	432	184	3.6		102	187.68	0.258	0.168	34 high	10 Good limit, spikey acceleration on eqs 1 and 2	
Model 3b, 2	2	50	466	198	5.4		90	178.2	0.124	0.081	49 med	16 Calibration adjusted to bring into line with ppt2	1/5/98, Ref 8
Model 3b, 2	2	50	469	200	5.7		90	180	0.124	0.081	49 high	2 Good record	525mm depth
Model 3b, 2	2	50	528	228	4.5		82	186.96	0.117	0.076	49 high	11 Clearly reached limit	49% loose, 77% dense
Model 3b, 2	2	50	385	164	25.1		90	147.6	0.132	0.086	49 high	1 Just reached limit	
Model 3b, 3	3	50	466	190	5.2		85	161.5	0.135	0.088	50 med	16 Calibration adjusted to bring into line with ppt2	
Model 3b, 3	3	50	469	197	4.9		90	177.3	0.135	0.088	50 high	2 Good record	
Model 3b, 3	3	50	528	220	6.5		66	145.2	0.127	0.083	50 high	11 Clearly reached limit	
Model 3b, 3	3	50	385	164	19.7		90	147.6	0.144	0.093	50 high	1 Just reached limit	
Model 3c, 1	1	50	457	194	4.3	1.0	100	194	0.225	0.146	50 *	30 Excellent, exactly 100%, less than 1 cycle to 50% query amplitude	5/5/98, Ref 7
Model 3c, 1	1	50	468	196	4.1	1.2	100	196	0.228	0.148	50 *	31 Excellent, again exactly 100%	525mm depth
Model 3c, 1	1	50	524	222	4.2	1.2	95	210.9	0.216	0.141	50 *	10 Excellent	49% loose, 79% dense
Model 3c, 1	1	50	296	130	17.6	2.2	87	113.1	0.247	0.161	75 high	11 Limit rises slowly	
Model 3c, 1	1	50	320	129	14.9	1.9	90	116.1	0.268	0.174	75 high	16 Limit rises slowly	
Model 3c, 1	1	50	382	160	7.5	1.2	100	160	0.243	0.158	75 high	15 Rapid rise time, liquefaction could be affected by loose layer below	
Model 3c, 1	1	50	115	53.5	5.4	2.1	84	44.94	0.3	0.195	75 high	5 Clear limit, noisy record affects 50%	
Model 3c, 1	1	50	123	54	6.8	1.9	96	51.84	0.315	0.205	75 high	2 Clear limit, noisy record affects 50%	
Model 3c, 1	1	50	252	100	9.5	1.7	96	96	0.296	0.192	75 high	1 Limit rises slowly affects 50%	
Model 3c, 2	2	50	457	194	6.5		98	190.12	0.218	0.142	50 high	30 Rapid rise to 90% +	
Model 3c, 2	2	50	468	196	5.7		96	188.16	0.221	0.143	50 high	31 Very rapid rise to 90% +	
Model 3c, 2	2	50	524	222	12.0		92	204.24	0.209	0.136	50 med	10 First limit reached at 82%, then rose to 92%	

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Model													Comment	Notes
Model 3c, 2	2	50	296	130	37.8		90	117	0.239	0.156	76 low		11 Still climbing slowly at end of shaking	
Model 3c, 2	2	50	320	129	36.8		92	118.68	0.26	0.169	75 low		16 Still climbing slowly at end of shaking	
Model 3c, 2	2	50	382	160	21.6		100	160	0.235	0.153	75 high		15 Reached limit, probably influenced by loose layer below	
Model 3c, 2	2	50	115	53.5	24.3		77	41.195	0.29	0.189	75 high		5 Clear limit, noisy record	
Model 3c, 2	2	50	123	54	32.4		83	44.82	0.305	0.198	75 high		2 Clear limit, noisy record	
Model 3c, 2	2	50	252	100	31.1		95	95	0.286	0.186	75 high		1 Close to 100% at end of shaking	
Model 3c, 2	2	50	457	194	8.1		97	188.18	0.207	0.134	50 high		30 Rapid rise to 80% +	
Model 3c, 3	3	50	468	196	7.6		98	192.08	0.209	0.136	50 high		31 Very rapid rise to 90% +	
Model 3c, 3	3	50	524	222	15.3		95	210.9	0.199	0.129	50 med		10 Again, double stage rise, as eq2	
Model 3c, 3	3	50	296	130	44.3		92	119.6	0.227	0.148	75 low		11 Still climbing slowly at end of shaking	
Model 3c, 3	3	50	320	129	45.9		93	119.97	0.246	0.16	75 low		16 Still climbing slowly at end of shaking	
Model 3c, 3	3	50	382	160	22.7		100	160	0.223	0.145	75 high		15 Probably influenced by loose layer below	
Model 3c, 3	3	50	115	53.5	24.3		76	40.66	0.275	0.179	75 high		5 Clear limit, noisy record	
Model 3c, 3	3	50	123	54	23.0		82	44.28	0.29	0.188	75 high		2 Clear limit, noisy record	
Model 3c, 3	3												1 Still rising at end of shaking	
Model 3d, 1	1	125	434	226	8.6	4.9	63	142.38	0.147	0.09	54 *		48 Excellent	3/9/98, Ref 11
Model 3d, 1	1	125	515	245	17.6	4.9	78	191.1	0.147	0.095	54 med		37 Slow buildup makes definition of limit difficult	525mm depth
Model 3d, 1	1	125	522	243	12.4	3.4	75	182.25	0.149	0.097	54 high		35 Slow buildup makes definition of limit difficult	54% loose, 80% dense
Model 3d, 1	1	125	434	223	7.9	4.2	65	144.95	0.141	0.092	54 *		40 Excellent, cycles affect 50%	
Model 3d, 1	1												38 Still climbing at end of shaking	
Model 3d, 1	1												44 Still climbing at end of shaking	
Model 3d, 2	2	125	523	283	14.8		70	198.1	0.163	0.106	54 high		37 Rapid rise to 60%, then slow climb	
Model 3d, 2	2	125	522	273	11.8		73	199.29	0.169	0.11	54 high		35 Rapid rise to 60%, then slow climb	
Model 3d, 2	2												48 Still climbing slowly at end of shaking	
Model 3d, 2	2												40 Still climbing at end of shaking	
Model 3d, 2	2												38 Still climbing at end of shaking	
Model 3d, 2	2												44 Still climbing at end of shaking	
Model 3d, 3	3	125	523	283	8.0		70	198.1	0.168	0.109	54 high		37 Good record	
Model 3d, 3	3	125	522	273	8.5		75	204.75	0.174	0.113	54 high		35 Good record	
Model 3d, 3	3												48 Still climbing slowly at end of shaking	
Model 3d, 3	3												40 Still climbing at end of shaking	
Model 3d, 3	3												38 Still climbing at end of shaking	
Model 3d, 3	3												44 Still climbing at end of shaking	
Model 3d, 4	4	125	508	268	28.6		72	192.96	0.182	0.118	54 high		37 Two stage rise	
Model 3d, 4	4	125	522	273	27.2		70	191.1	0.184	0.12	54 high		35 Two stage rise	
Model 3d, 4	4	125	435	257	28.1		62	159.34	0.171	0.111	54 high		48 Clear limit	
Model 3d, 4	4	125	438	257	25.9		61	156.77	0.172	0.112	54 high		40 Clear limit	
Model 3d, 4	4												38 Still climbing at end of shaking	
Model 3d, 4	4												44 Still climbing at end of shaking	
Model 3e, 1	1	50	521	235	10.9		100	235	0.652	0.424	50 *		35 Classic rise to 100%, some cycling at limit	3/10/01, Ref 35
Model 3e, 1	1	50	369	170							75		39 Noisy, no clear limit, steady rise	525mm depth
Model 3e, 1	1	50	239	239							75		43 u/s	50% loose, 75% dense
Model 3e, 1	1	50	359	359							50		48 u/s	No surcharge on flight 1
Model 3e, 1	1	50	105	105	21.2		88	92	0.828	0.538	75 *		56 Classic response to near 100%	50g
Model 3e, 1	1	50	108	67	18.8		85	57	0.716	0.465	75 high		57 Good rsponse, slightly noisy	See also Model 5g
Model 3f, 1	1	100	471	191	9.4		93	178	0.341	0.222	50 *		35 Classic rise to limit near 100%, noisy	16/10/01, Ref 37
Model 3f, 1	1	100	394	426							50		39 Static pore pressure u/s	282mm depth
Model 3f, 1	1	100	316	131							75		56 Steady climb	50% loose, 75% dense
Model 3f, 1	1	100	375	169	4.1		54	91	0.327	0.213	75 high		57 Quick rise to early limit, flat then slow climb	No surcharge
														100g
Model 4a, 1	1	50	477	347	24.8	14.0	80	278	0.078	0.051	49 high		45 Clearly reached upper limit	14/9/98, Ref 12

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Model										Note	Description	Remarks
Model 4a, 1	1	50	483	26.7	22.1	75	0.078	0.051	49 high	35	Clearly reached upper limit	525mm depth
Model 4a, 1	1									52	Still climbing at end of shaking	49% loose, 80% dense
Model 4a, 1	1									43	Still climbing at end of shaking	
Model 4a, 2	2	50	469	40		27	0.098	0.064	49 med	45	Reached some sort of limit, much less than eq1	
Model 4a, 2	2	50	474	40		16	0.098	0.064	49 med	35	Reached some sort of limit, much less than eq1	
Model 4a, 2	2									52	Still climbing at end of shaking	
Model 4a, 2	2									43	Still climbing at end of shaking	
Model 4a, 3	3									45	Very little excess pore pressure generated	
Model 4a, 3	3									35	Very little excess pore pressure generated	
Model 4a, 3	3									52	Very little excess pore pressure generated	
Model 4a, 3	3									43	Very little excess pore pressure generated	
Model 4a, 4	4									45	No excess pore pressure at all	
Model 4a, 4	4									35	No excess pore pressure at all	
Model 4a, 4	4									52	No excess pore pressure at all	
Model 4a, 4	4									43	No excess pore pressure at all	
Model 4b, 1	1	125	465	24.4		85	0.165	0.107	56 low	39	Very noisy signal, minimal excess pore pressure	15/9/98, Ref 13
Model 4b, 1	1									40	Very noisy signal, minimal excess pore pressure	525mm depth
Model 4b, 1	1									44	Very noisy signal, minimal excess pore pressure	56% loose, 74% dense
Model 4b, 2	2									39	Clear limit, surprising after eq1	
Model 4b, 2	2									40	Climbing at end of earthquake	
Model 4b, 2	2									44	Climbing at end of earthquake	
Model 4b, 3	3									39	No excess pore pressure at all	
Model 4b, 3	3									40	Almost no excess pore pressure	
Model 4b, 3	3									44	Climbing at end of earthquake	
Model 4b, 4	4									39	No excess pore pressure at all	
Model 4b, 4	4									40	Almost no excess pore pressure	
Model 4b, 4	4									44	Almost no excess pore pressure	
Model 4c, 1	1	50	808	19.5	13.338	60	0.073	0.048	50 high	51	Good record : (6 other ppts in upper layer showed	22/10/98, Ref 17
Model 4c, 1	1	50	806	20.6	15.903	59	0.073	0.048	50 high	38	Good record : no response in any Model 4c eq)	525mm depth
Model 4c, 1	1									47	Still climbing at end of shaking	50% loose, 75% dense
Model 4c, 1	1									46	Still climbing at end of shaking	292 lb surcharge
Model 4c, 1	1									50	Still climbing at end of shaking	
Model 4c, 1	1									41	Still climbing at end of shaking	
Model 4c, 2	2									51	Still climbing at end of shaking	
Model 4c, 2	2									38	Still climbing at end of shaking	
Model 4c, 2	2									47	Still climbing at end of shaking	
Model 4c, 2	2									46	Still climbing at end of shaking	
Model 4c, 2	2									50	Still climbing at end of shaking	
Model 4c, 2	2									41	Still climbing at end of shaking	
Model 4c, 3	3									51	Still climbing at end of shaking	
Model 4c, 3	3									38	Still climbing at end of shaking	
Model 4c, 3	3									47	Still climbing at end of shaking	
Model 4c, 3	3									46	Still climbing at end of shaking	
Model 4c, 3	3									50	Still climbing at end of shaking	
Model 4c, 3	3									41	Still climbing at end of shaking	
Model 4c, 4	4									51	Almost no excess pore pressure	
Model 4c, 4	4									38	Almost no excess pore pressure	
Model 4c, 4	4									47	Almost no excess pore pressure	
Model 4c, 4	4									46	Almost no excess pore pressure	
Model 4c, 4	4									50	Almost no excess pore pressure	
Model 4c, 4	4									41	Almost no excess pore pressure	

Model	#	C1	C2	C3	C4	C5	C6	C7	C8	C9	Description	Notes
Model 4d, 1	1	125	813	543	11.9	47	255.21	0.079	0.051	50 high	38 Excellent: (6 ppts in upper layer showed	4/11/98, Ref 18
Model 4d, 1	1	125	813	543	12.42	48	260.64	0.079	0.051	50 high	51 Excellent: almost no response in any 4d eq)	525mm depth
Model 4d, 1	1										47 Climbing at end of earthquake	50% loose, 88% dense
Model 4d, 1	1										46 Climbing at end of earthquake	292 lb surcharge
Model 4d, 1	1										50 Still climbing at end of shaking	
Model 4d, 1	1										41 Still climbing at end of shaking	
Model 4d, 2	2	125	813	543	12.4	44	238.92	0.085	0.055	50 high	38 Good record	
Model 4d, 2	2	125	813	543	11.8	45	244.35	0.085	0.055	50 high	51 Good record	
Model 4d, 2	2										47 Climbing at end of earthquake	
Model 4d, 2	2										46 Climbing at end of earthquake	
Model 4d, 2	2										50 Still climbing slowly at end of shaking	
Model 4d, 2	2										41 Still climbing slowly at end of shaking	
Model 4d, 3	3	125	813	543	47	37	200.91	0.083	0.054	50 med	38 Possible limit at end of shaking	
Model 4d, 3	3	125	813	543	47	38	206.34	0.083	0.054	50 med	51 Possible limit at end of shaking	
Model 4d, 3	3										47 Climbing at end of earthquake	
Model 4d, 3	3										46 Climbing at end of earthquake	
Model 4d, 3	3	125	739	515	37.9	41	211.15	0.083	0.054	50 high	50 Appears to reach limit near end of shaking	
Model 4d, 3	3	125	741	512	36	41	209.92	0.083	0.054	50 high	41 Appears to reach limit near end of shaking	
Model 4d, 4	4										38 Still climbing at end of shaking	
Model 4d, 4	4										51 Still climbing at end of shaking	
Model 4d, 4	4										47 Climbing at end of earthquake	
Model 4d, 4	4										46 Climbing at end of earthquake	
Model 4d, 4	4										50 Still climbing at end of shaking	
Model 4d, 4	4										41 Still climbing at end of shaking	
Model 4e, 1	1	50	738	430	20.2	87	374	0.439	0.285	50 *	39 Excellent early response	14/7/00, Ref 24
Model 4e, 1	1	50	648	415	30.6	77	320	0.418	0.270	50 high	38 Classic rise to near 100%	525mm depth
Model 4e, 1	1	50	505	337							50 Steady climb throughout duration	50% uniform density
Model 4e, 1	1	50	586	353	13.1	74	261	0.464	0.302	50 high	46 Rapid rise to early limit, slight increase later	211 lb surcharge
Model 4e, 1	1	50	439	310							6 Steady climb throughout duration	50, 80,100, 125g
Model 4e, 1	1	50	500	346							54 Steady climb throughout duration	
Model 4f, 1	1	50	313	267						low	1 No significant excess pore pressure	2/8/00, Ref 25
Model 4f, 1	1	50	220	220							8 u/s	525mm depth
Model 4f, 1	1	50	573	371	8.9	21	78	0.178	0.116	55 high	10 Quick rise to early limit, then flat	Densities uncertain
Model 4f, 1	1	50	555	555							16 u/s	211 lb surcharge
Model 4f, 1	1	50	728	445	12.4	89	396	0.173	0.112	55 *	38 Excellent response, absolutely flat limit	50, 80, 100, 125g
Model 4f, 1	1	50	472	379	9.5	24	91	0.15	0.098	55 med	39 Quick rise to limit, very noisy	Average RD = 54.7%
Model 4f, 1	1	50	431	431							14 u/s	
Model 4f, 1	1	50	424	314	13.6	17	53	0.171	0.111	55 high	41 Quick rise to limit, then flat	
Model 4f, 1	1	50	335	237						low	48 Very noisy	
Model 4f, 1	1	50	647	407	8.3	17	69	0.176	0.114	55 high	54 Quick rise to limit, then steady climb	
Model 4g, 1	1	50	698	342	8.1	101	345	0.273	0.177	50 *	53 Excellent early response, slight rise later	5,7/8/00, Ref 26
Model 4g, 1	1	50	562	383	4	19	73	0.206	0.134	50 high	43 Clear early limit, flat then long rise	525mm depth
Model 4g, 1	1	50	670	385	6.9	78	300	0.233	0.151	50 high	37 Good early rise to limit, then slow rise later	50% uniform density
Model 4g, 1	1	50	508	336	6.9	15	50	0.221	0.144	50 high	6 Good early rise to limit, then steady rise later	50, 80, 100, 125g
Model 4g, 1	1	50	751	403	10.4	81	326	0.24	0.156	50 high	35 Good early rise to limit, then slow climb, noisy	
Model 4g, 1	1	50	248	220						low	13 Rise, drop and rise	
Model 4g, 1	1	50	505	338	7.5	14	47	0.219	0.142	50 high	42 Good early rise, flat then steady climb	
Model 4g, 1	1	50	450	291	6.4	12	35	0.237	0.154	50 high	50 Good early rise, flat then steady climb	
Model 4g, 1	1	50	330	247							46 No significant excess pore pressure	
Model 4h, 1	1	50	631	446	31.5	81	361	0.183	0.119	48 high	43 Steady convex rise to limit	23/8/00, Ref 27
Model 4h, 1	1	50	511	335	6.7	20.6	69	0.216	0.140	51 high	53 Quick rise to early limit, drop and then steady rise to end	525mm depth

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Model											Description	Notes
Model 4h, 1	1	50	571	7.3	381	137	36	0.203	0.132	48 high	13 Quick rise to early limit, flat and then steady rise to end	211 lb surcharge
Model 4h, 1	1	50	432	10.1	317	63	20	0.202	0.131	51 high	50 Quick rise to limit	50% uniform density
Model 4h, 1	1	50	607		625						8 u/s	50, 80, 100, 125g
Model 4h, 1	1	50	219	14	229	78	34	0.172	0.112	51 med	10 Quick rise to limit, then steady fall	
Model 4h, 1	1	50	711	31.5	457	393	86	0.194	0.126	48 high	35 Rapid initial rise, then steady climb	
Model 4h, 1	1	50	624	29.8	452	398	88	0.179	0.116	48 med	48 Good but slow rise to high limit	
Model 4h, 1	1	50	322	11.2	263	28	10.6	0.199	0.129	51 med	41 Noisy, but clear limit, then slow rise	
Model 4h, 1	1	50	497	11.2	354	53	15	0.199	0.129	51 med	42 Clear limit, then flat and long steady rise	
Model 4i, 1	1	50	242		237					50 med	6 No excess pore pressure	25/8/00, Ref 28
Model 4i, 1	1	50	659	13.1	402	237	59	0.21	0.137	50 high	46 Good limit, held for about 0.2 sec before rising again	525mm depth
Model 4i, 1	1	50	431		452						38 u/s	211 lb surcharge
Model 4i, 1	1	50	656	13.7	407	277	68	0.206	0.134	50 high	39 Clear limit	50% uniform density
Model 4i, 1	1	50	574	8.7	370	144	39	0.208	0.135	50 high	54 Clear limit	50, 80, 100, 125g
Model 4i, 1	1	50	502	10.9	343	72	21	0.205	0.133	50 high	8 Clear limit	
Model 4i, 1	1	50	320	8.4	264	21	8	0.195	0.127	50 med	1 Very noisy, but clear limit	
Model 4i, 1	1	50	720		437						37 No limit, steady rise to 300kpa plus	
Model 4i, 1	1	50	376		401						14 u/s	
Model 4j, 1	1	50	593	8.6	342	260	76	0.251	0.163	50 high	48 Limit held for 0.2 secs before rising again	8/9/00, Ref 29
Model 4j, 1	1	50	445	4.5	296	104	35	0.238	0.155	50 high	54 Limit held for about 0.1 secs before rising	525mm depth
Model 4j, 1	1	50	518	11.2	323	131	40.6	0.242	0.157	50 high	43 Limit held for about 0.1 secs before rising	211 lb surcharge
Model 4j, 1	1	50	330		244						6 No clear early limit, but steady rise	50% uniform density
Model 4j, 1	1	50	333		240						46 No clear early limit, but steady rise	50, 80, 100, 125g
Model 4j, 1	1	50	670	15.9	390	339	87	0.237	0.154	50 high	37 Note 70% at 4.1 cycles, rising to 97% at 42.8 cycles	
Model 4j, 1	1	50	736	36	412	342	83	0.238	0.155	50 high	35 Sharp early rise, then slow rise to final limit	
Model 4j, 1	1	50	238	15.6	211	17	8.2	0.214	0.139	50 high	42 Pretty much constant over the duration	
Model 4j, 1	1	50	669	83	387	105	27.1	0.239	0.155	50 high	39 Sharp early rise to 50% plus, then slow rise to limit	
Model 4j, 1	1	50	519	29	317	14	4.4	0.248	0.161	50 high	50 Limit at 28%, but then rose steadily later	
Model 4k, 1	1	50	232	21	91	98	108	0.401	0.261	48 high	41 Very rapid rise to c. 60% then slower rise to 100%	14/9/00, Ref 30
Model 4k, 1	1	50	447	14	193	174	90	0.299	0.194	50 high	10 Rise to 80% in 5.1 cycles, then slower rise to 90/100%	525 mm depth
Model 4k, 1	1	50	515								16 u/s	No surcharge
Model 4k, 1	1	50	521	16.4	226	199	88	0.284	0.185	50 high	1 Steady rise to 88/100%	50% uniform density
Model 4k, 1	1	50	455	4.9	179	179	100	0.328	0.213	50 *	13 Straight to 100% exactly	50, 80, 100, 125g
Model 4k, 1	1	50	313	7	109	89	82	0.42	0.273	48 high	53 Straight to 82%, then later to 130%	
Model 4k, 1	1	50	298	26.3	131	114	87	0.332	0.216	48 high	8 Rise to 60% in 5 cycles, then slower rise to 90/100%	
Model 4k, 1	1	50	38	13	15	16	106	0.581	0.378	48 high	46 Very noisy, but straight to 100%	
Model 4k, 1	1	50	113	20	50	40	80	0.423	0.275	48 high	42 Good steady rise to high limit	
Model 4l, 1	1	50	510	32	388	81	21	0.62	0.403	54 med	53 Initial limit, but noisy and slowly continued to climb	15/2/01, Ref 33
Model 4l, 1	1	50	394		339						46 Steady climb	525 mm depth
Model 4l, 1	1	50	813		515						37 Steady climb	295 lb surcharge
Model 4l, 1	1	50	648	52	446	80	18	0.631	0.410	54 med	43 Initial good rise, then upper limit reached very slowly	Densities uncertain
Model 4l, 1	1	50	732		481						48 Steady climb	Average used here
Model 4l, 1	1	50	582	25	418	67	16	0.628	0.408	54 med	41 Good upper limit	
Model 4l, 1	1	50	732		481						39 Noisy, steady climb	
Model 4l, 1	1	50	813		515						35 Noisy, steady climb	
Model 5a, 1	1	50	1101	13.9	14.067	823	411.5	50	0.055	0.036	51 high	51 Shows double frequencies : (note upper 4 pds showed minimal)	7/10/98, Ref 15
Model 5a, 1	1	50	1105	15	13.419	825	412.5	50	0.055	0.036	51 high	38 Shows double frequencies : dynamic response) only just reached 50%	525mm depth
Model 5a, 1	1	50	1040	34		797	239.1	30	0.055	0.036	51 low	41 Still climbing slowly at end of shaking	586 lb surcharge
Model 5a, 1	1	50	1038	34		797	247.07	31	0.055	0.036	51 low	50 Still climbing slowly at end of shaking	51% loose, 72% dense
Model 5a, 1	1										13 Still climbing at end of shaking	
Model 5a, 1	1										11 Still climbing at end of shaking	
Model 5a, 1	1										47 Still climbing at end of shaking	

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Model	Grp								Description
Model 5a, 1	1								46 Still climbing at end of shaking
Model 5a, 2	2	50	1113	824	30.9	337.84	0.056	0.036	51 high — 51 Reaches limit showing double frequency behaviour
Model 5a, 2	2	50	1113	825	30.9	321.75	0.056	0.036	51 high — 38 Note strong double frequency behaviour
Model 5a, 2	2	50	1044	799	35	191.76	0.056	0.036	51 med — 41 Just reached limit
Model 5a, 2	2	50	1047	805	35	209.3	0.055	0.036	51 med — 50 Just reached limit
Model 5a, 2	2								13 Still climbing at end of shaking
Model 5a, 2	2								11 Still climbing at end of shaking
Model 5a, 2	2								47 Still climbing at end of shaking
Model 5a, 2	2								46 Still climbing at end of shaking
Model 5a, 3	3								51 Still climbing slowly at end of shaking
Model 5a, 3	3								38 Still climbing slowly at end of shaking
Model 5a, 3	3								41 Still climbing at end of shaking
Model 5a, 3	3								50 Still climbing at end of shaking
Model 5a, 3	3								13 Still climbing at end of shaking
Model 5a, 3	3								11 Still climbing at end of shaking
Model 5a, 3	3								47 Still climbing at end of shaking
Model 5a, 3	3								46 Still climbing at end of shaking
Model 5a, 4	4								51 Very small excess pore pressure, still climbing at end
Model 5a, 4	4								38 Very small excess pore pressure, still climbing at end
Model 5a, 4	4								41 Still climbing at end of shaking
Model 5a, 4	4								50 Still climbing at end of shaking
Model 5a, 4	4								13 Almost no excess pore pressure
Model 5a, 4	4								11 Almost no excess pore pressure
Model 5a, 4	4								47 Still climbing at end of shaking
Model 5a, 4	4								46 Still climbing at end of shaking
Model 5b, 1	1	50	1118	830	20	273.9	0.068	0.044	49 high — 51 Reaches limit which rises slowly : (note 6 ppts in upper layer showed
Model 5b, 1	1	50	1119	830	18.25	282.2	0.068	0.044	49 high — 38 Reaches limit which rises slowly : no dynamic excess pore pressure)
Model 5b, 1	1								47 Very little excess pore pressure
Model 5b, 1	1								46 Very little excess pore pressure
Model 5b, 1	1	50	1043	801					50 Rising steadily at end of shaking
Model 5b, 1	1	50	1042	799					41 Rising steadily at end of shaking
Model 5b, 2	2								51 Rising steadily at end of shaking
Model 5b, 2	2								38 Rising steadily at end of shaking
Model 5b, 2	2								47 Rising steadily at end of shaking
Model 5b, 2	2								46 Rising steadily at end of shaking
Model 5b, 2	2								50 Rising steadily at end of shaking
Model 5b, 2	2								41 Rising steadily at end of shaking
Model 5b, 3	3								51 Small excess pore pressure, rising steadily at end of shaking
Model 5b, 3	3								38 Small excess pore pressure, rising steadily at end of shaking
Model 5b, 3	3								47 Small excess pore pressure, rising steadily at end of shaking
Model 5b, 3	3								46 Small excess pore pressure, rising steadily at end of shaking
Model 5b, 3	3								50 Almost no excess pore pressure, slight rise at end of shaking
Model 5b, 3	3								41 Almost no excess pore pressure, slight rise at end of shaking
Model 5b, 4	4								51 Very little excess pore pressure
Model 5b, 4	4								38 Very little excess pore pressure
Model 5b, 4	4								47 Almost no excess pore pressure
Model 5b, 4	4								46 Almost no excess pore pressure
Model 5b, 4	4								50 Very little excess pore pressure
Model 5b, 4	4								41 Very little excess pore pressure
Model 5c, 1	1								46 Almost no excess pore pressure, noisy signal
Model 5c, 1	1								47 Almost no excess pore pressure, noisy signal

Notes (Model 5a block): 14/9/98, Ref 16; 525mm depth; 586 lb surcharge; 49% loose, 76% dense; 125, then 50g

Notes (Model 5c block): 11/12/98, Ref 19; 525mm depth

Model	No.	g									Class	Observation	Notes
Model 5c, 1	1											41 Still climbing at end of shaking	775 lb surcharge
Model 5c, 1	1											50 Still climbing at end of shaking	52% loose, 75% dense
Model 5c, 1	1											38 Starting to climb steeply at end of shaking	50g
Model 5c, 1	1											51 Starting to climb steeply at end of shaking	
Model 5c, 2	2											46 Climbing at end of earthquake	
Model 5c, 2	2											47 Climbing at end of earthquake	
Model 5c, 2	2											41 Climbing at end of earthquake	
Model 5c, 2	2											50 Climbing at end of earthquake	
Model 5c, 2	2											38 Climbing steeply at end of shaking	
Model 5c, 3	3											51 Climbing steeply at end of shaking	
Model 5c, 3	3											46 Climbing at end of earthquake	
Model 5c, 3	3	50	1222	974								47 Climbing at end of earthquake	
Model 5c, 3	3	50	1221	975								41 Climbing at end of shaking, but possible flat top just at end	
Model 5c, 3	3	50	1291	1009								50 Climbing at end of shaking at end of earthquake; 38 Climbing steadily at end of shaking	
Model 5c, 3	3	50	1291	1009	28		17	171.53	0.042	0.028	52 low	51 Climbing at end of shaking, but possible flat top just at end	
Model 5d,1	1	50	1223	978	47.3	34.4	33	322.74	0.092	0.06	39 high	31 Filtered acceleration record : (note 6 ppts in upper layer showed	17/12/99, Ref 20
Model 5d,1	1	50	1217	985	37	26.918	35	344.75	0.091	0.059	39 high	43 Filtered acceleration record : no significant response during shaking)	525mm depth
Model 5d,1	1	50	1280	1037	34.4	22.79	52	539.24	0.088	0.047	39 high	39 Filtered acceleration record	775 lb surcharge
Model 5d,1	1	50	1125									13 Climbing at end of shaking	57% loose, 80% dense
Model 5e, 1	1	50	1140	925								37 Initial limit around 27%, then drift upwards	10/7/00, Ref 23
Model 5e, 1	1	50	1224	900								43 Initial limit around 25%, then drift upwards	525mm depth
Model 5e, 1	1	50	1070	911	31.3		50	456	0.203	0.132	50 high	35 Good response, clear flat top	708 lb surcharge
Model 5e, 1	1	50	1012	851								10 Less than 5%, then steady drift upwards	50% density, assumed
Model 5f, 1	1	50	724	722	17.6		61	440	0.569	0.370	50 high	35 Good response, with cycles at upper limit	31/8/01, Ref 34
Model 5f, 1	1	50	784									48 u/s	525mm depth
Model 5f, 1	1	50	661									43 u/s	495 lb surcharge
Model5f, 1	1	50	865									37 u/s; 39 u/s	50% loose, 74% dense; 50g
Model 5g, 1	1	50	1021	712	16.4		74	527	0.247	0.161	48 high	35 Shows strong cyclic behaviour	4/10/01, Ref 35
Model 5g, 1	1	50	870	645	14.5		46.5	300	0.249	0.162	48 med	39 Quite noisy, but clearly limited response	525mm depth
Model 5g, 1	1	50	730									43 u/s	495 lb surcharge on 2nd flight only (eq2)
Model 5g, 1	1	50	850									48 u/s	48% loose, 74% dense
Model 5g, 1	1	50	733	579	7.9		11.5	67	0.251	0.163	74 med	56 Very low response, with drop after peak	50g, 2 flights
Model 5g, 1	1	50	610	540	12.7		8	43	0.239	0.155	74 med	57 Very low response, but clear flat top upper limit	
Model 5h, 1	1	125	1285	607	14.4		97	589	0.243	0.158	49 high	35 Sharp rise to liquefaction	11/10/01, Ref 36
Model 5h, 1	1	125	733	384								57 Rapid initial rise, then steady climb	525mm depth
Model 5h, 1	1	125	954	374								48 u/s	No surcharge
Model 5h, 1	1	125	554	317								56 Very noisy signal, appears to be climbing	49% loose, 74% dense
Model 5h, 1	1	125	1119	546	13.6		97	530	0.251	0.163	49 high	39 Only marred by uncertain static pore pressure	125g
Model 5i, 1	1	125	597	581								10374 Characterised by falling acceleration input. Depth of phreatic	14/11/01, Ref 39
Model 5i, 1	1	125	737	740								10375 surface probably closer to 390mm deep, rather than the intended	460mm total depth
Model 5i, 1	1	125	473	437								10376 250mm, hence 10374-10378 probably unsaturated.	No surcharge, 64mm
Model 5i, 1	1	125	695	645								10378	50% loose, 75% dense
Model 5i, 1	1	125	803	800	38		32	256	0.115	0.075	50 med	10379 Delayed peak due to redistribution	phreatic surface at
Model 5i, 1	1	125	881	839	16		50	420	0.116	0.075	50 high	56 Good rise to peak	250mm depth, 125g
Model 5i, 1	1	125	934	835	11		64	534	0.122	0.079	50 high	57 Strong rise to peak	

APPENDIX B

SUMMARY OF DATA

Time histories of acceleration, excess pore pressure and model configurations
Stress and strain histories

No recorded PPT Data

Cross-section through Model 2a   50 G

Model 2a

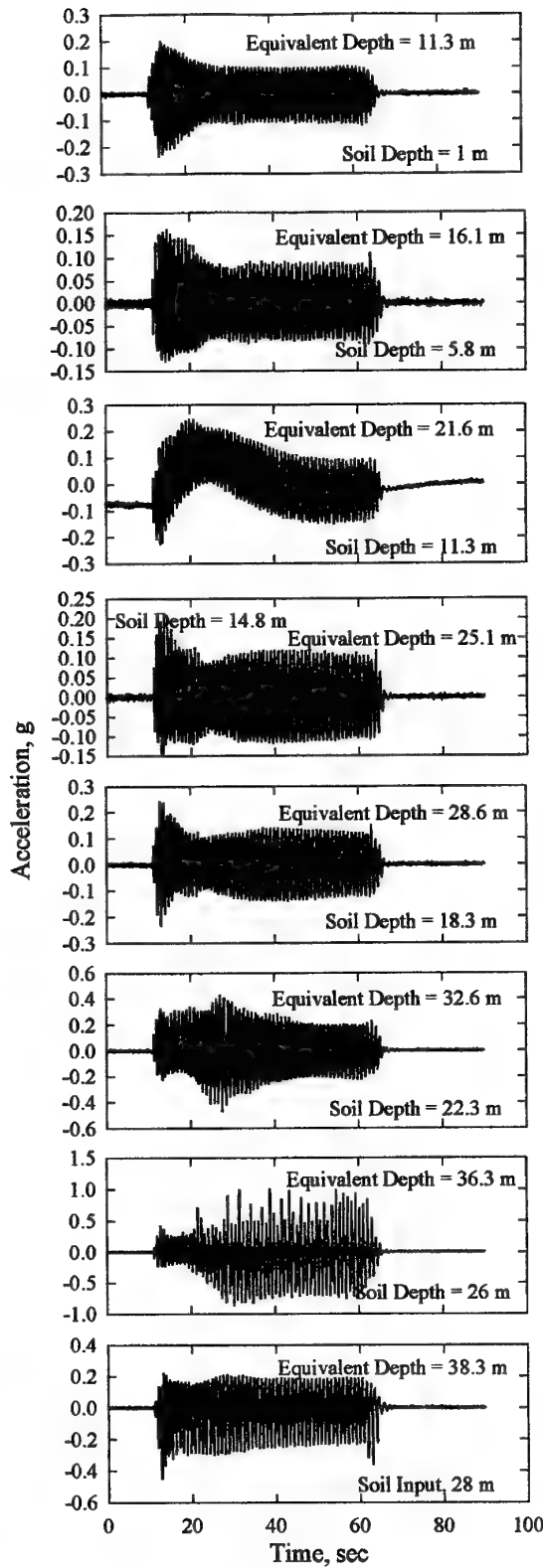## Model 2a-eq1

Cyclic Stress Ratio

Model 2a-eq1
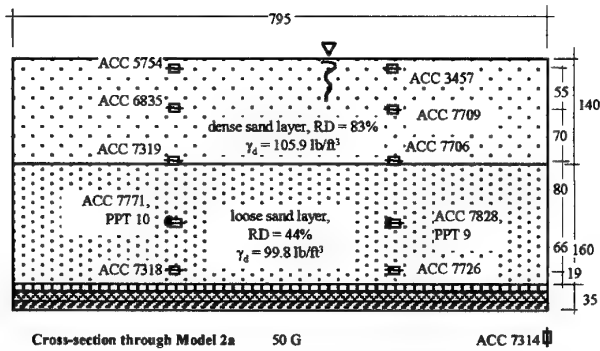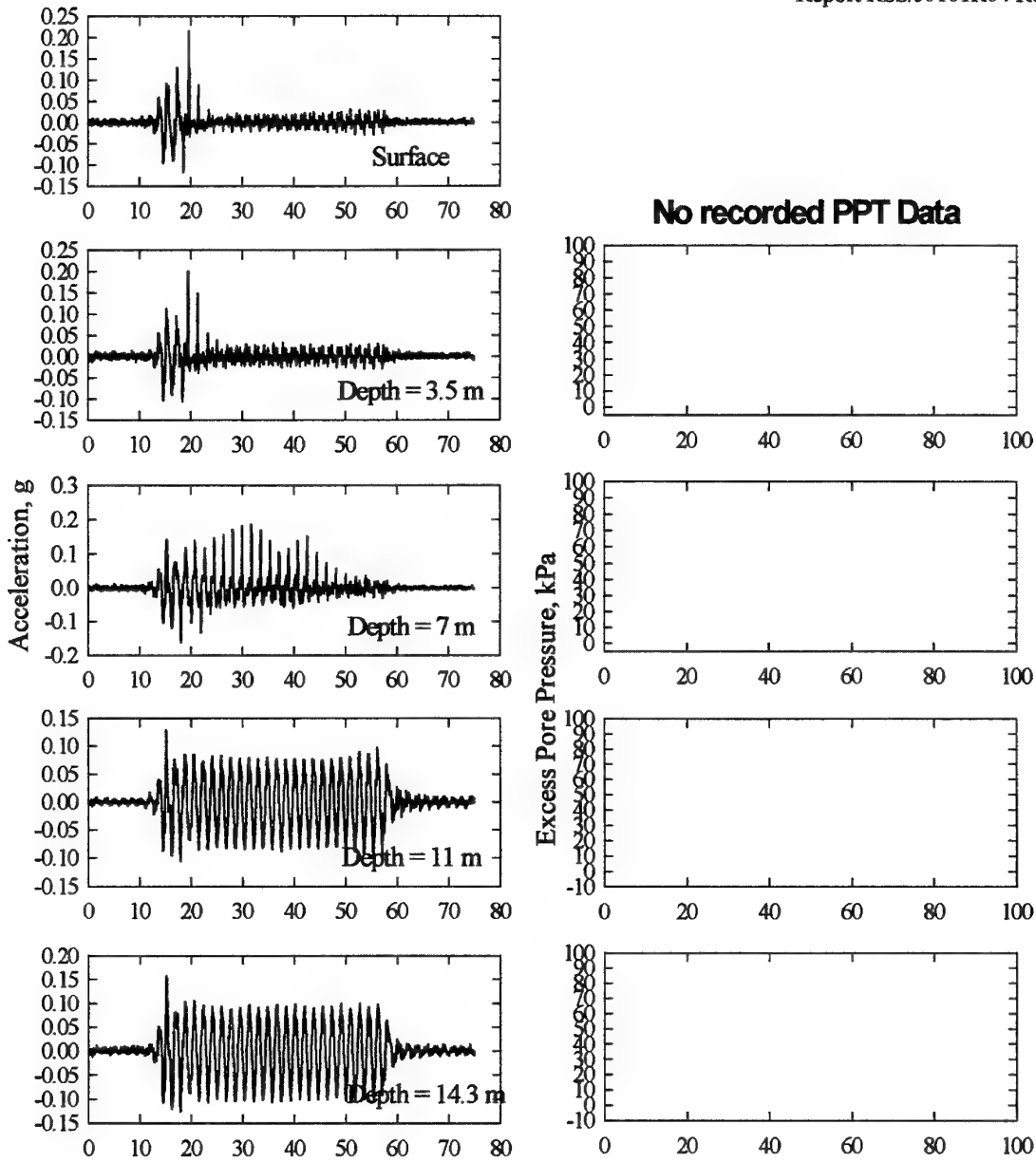
Cyclic Shear Strain, %
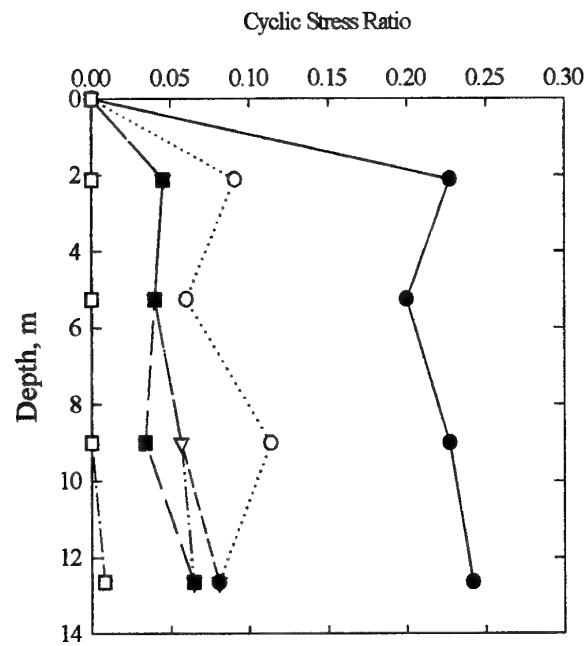
Model 2a-eq1
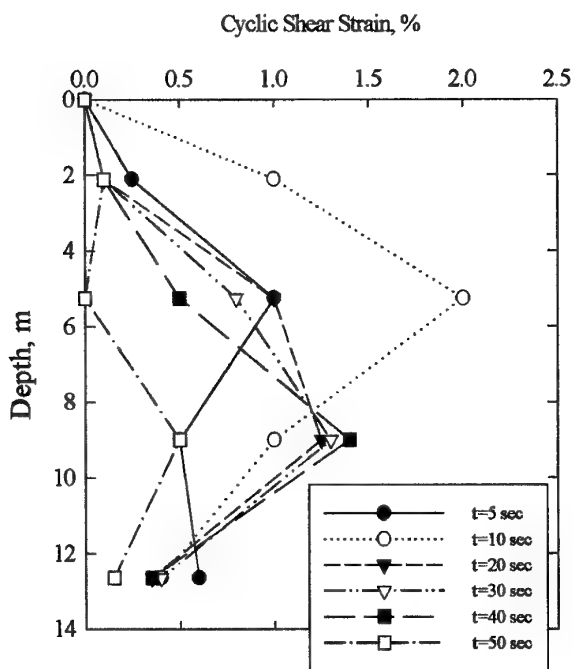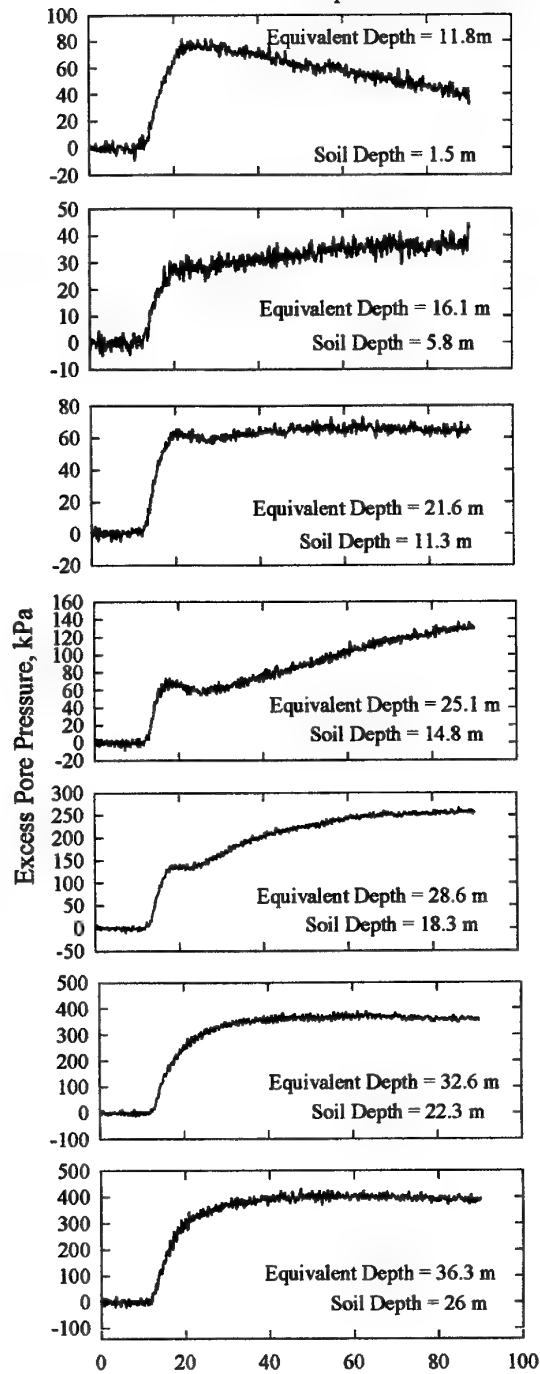
Cyclic Shear Stress, kPa
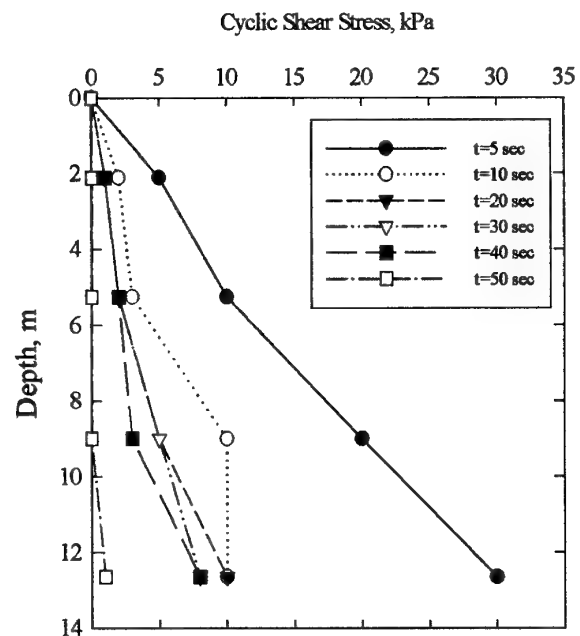
Model 2a Stress and strain isochrones

Model 2b

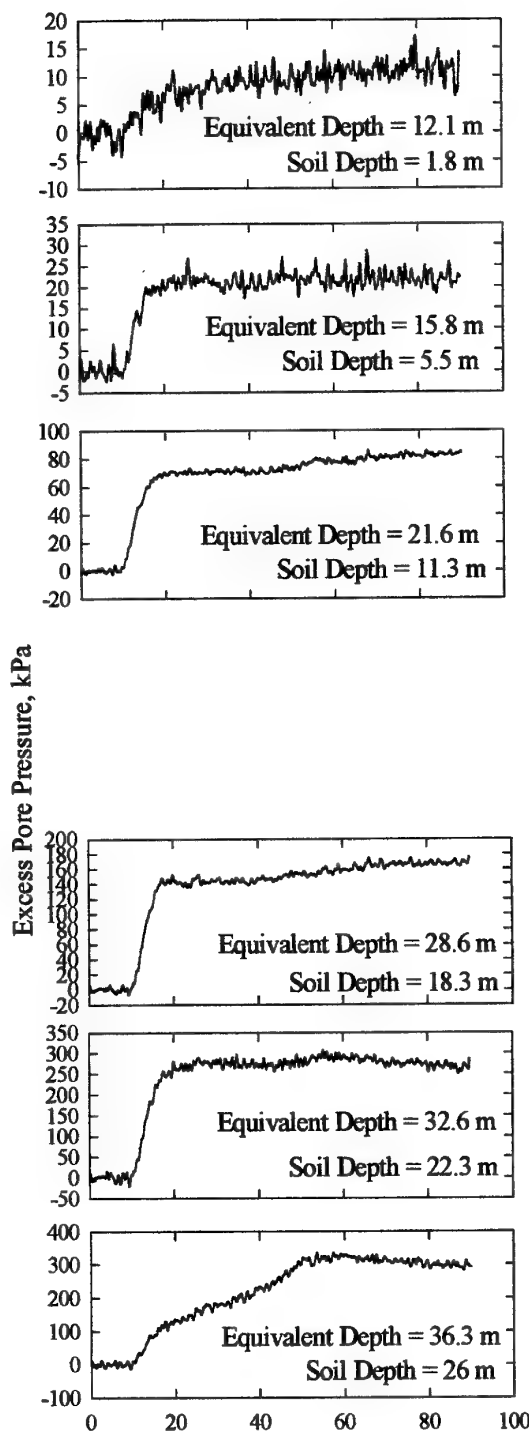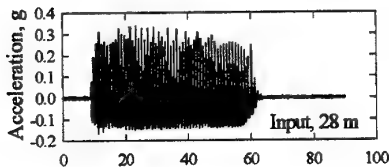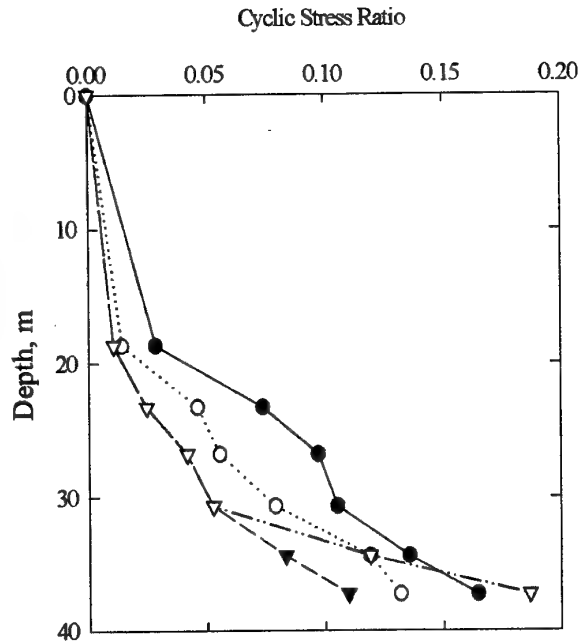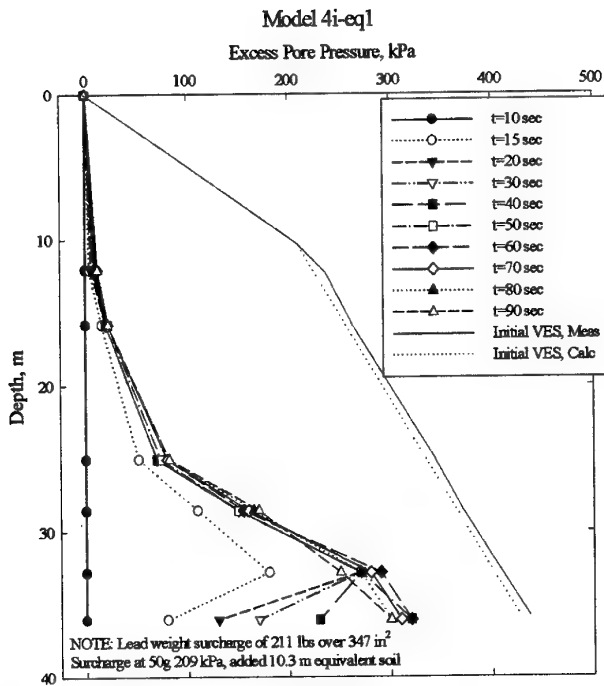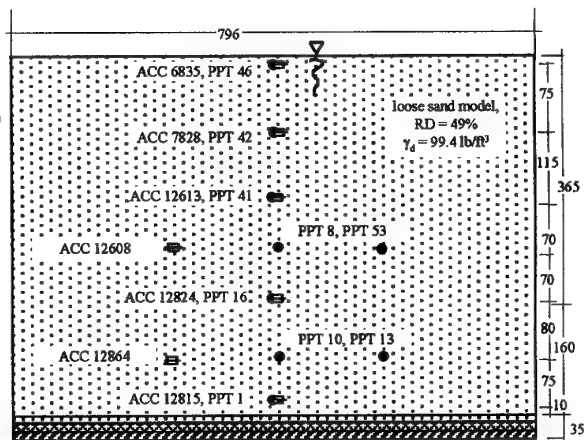Model 2b-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

f = 0.6 Hz
a_{max} = 0.08 g

Input 15 m
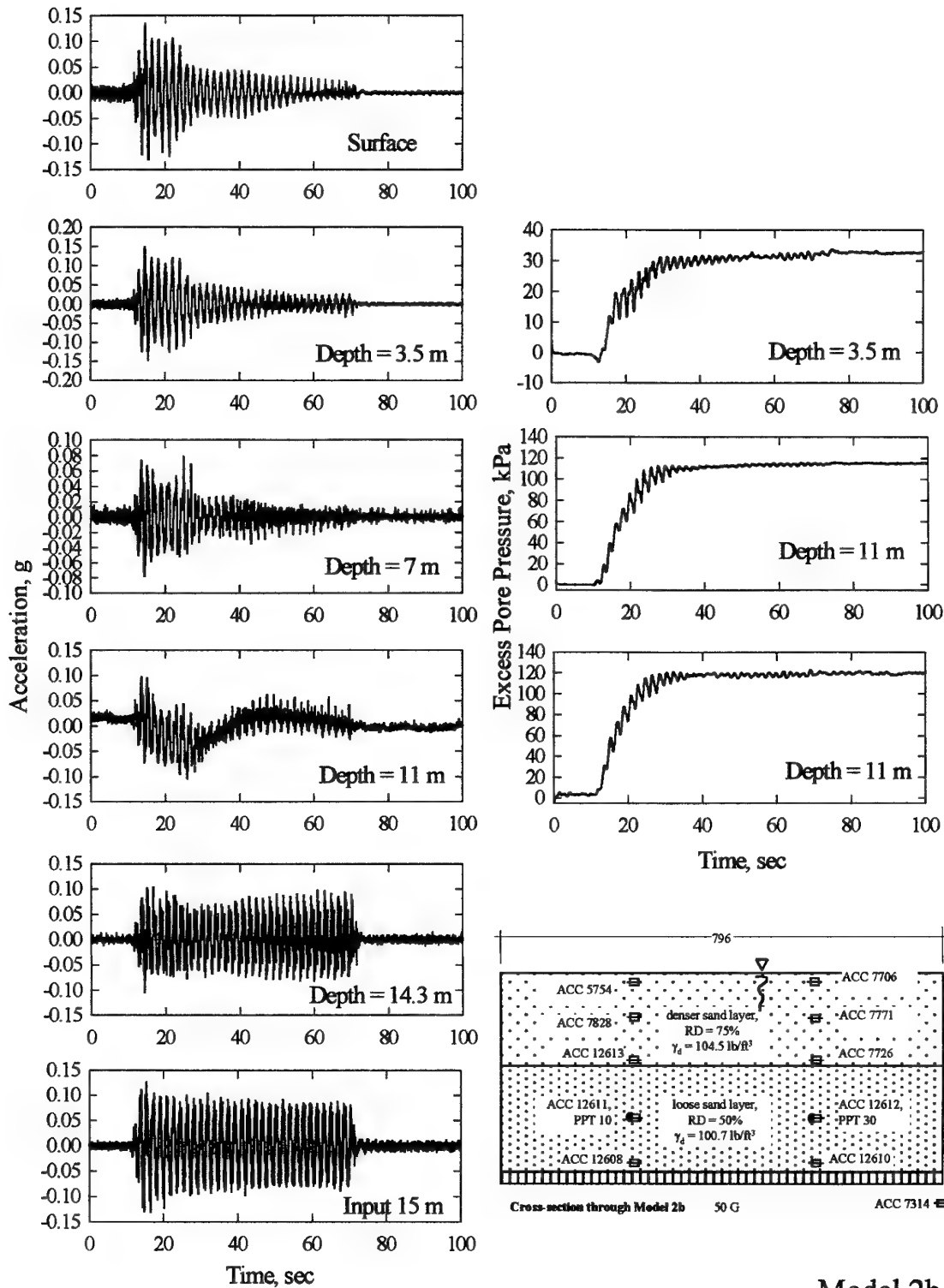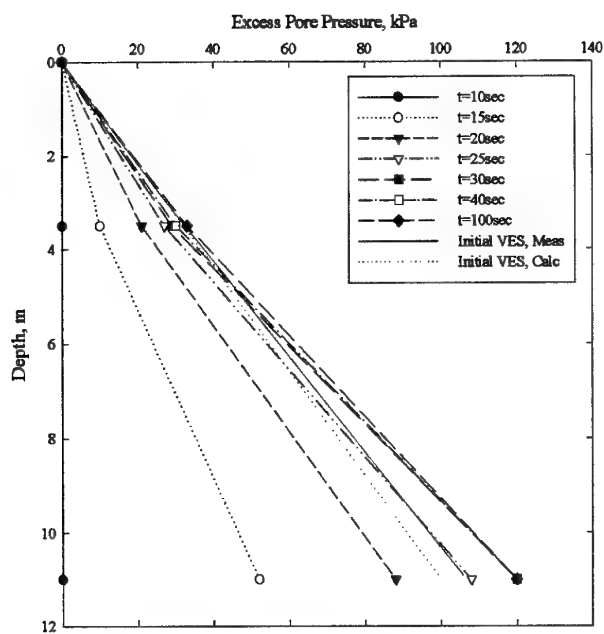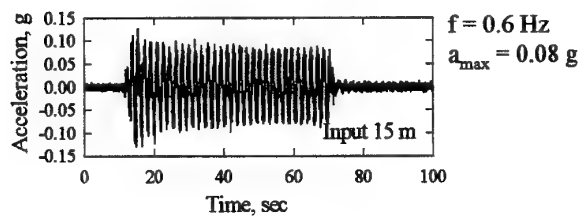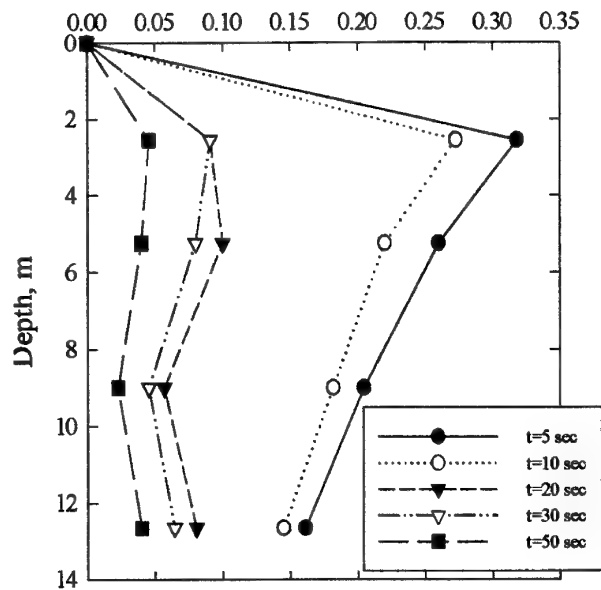
Model 2b-eq1

Cyclic Shear Strain, %
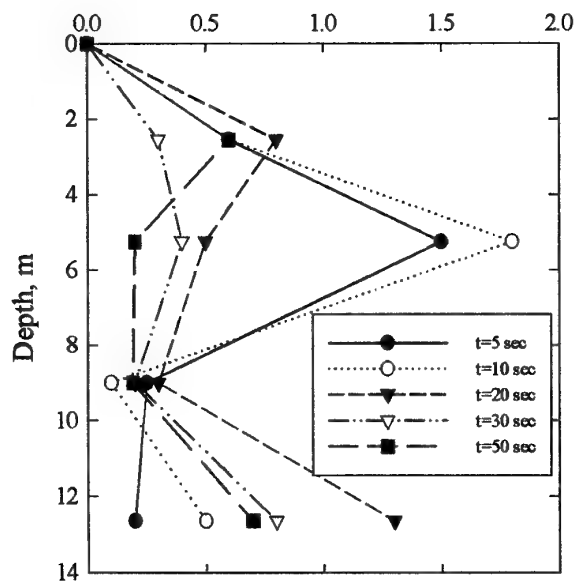
Model 2b-eq1

Cyclic Shear Stress, kPa
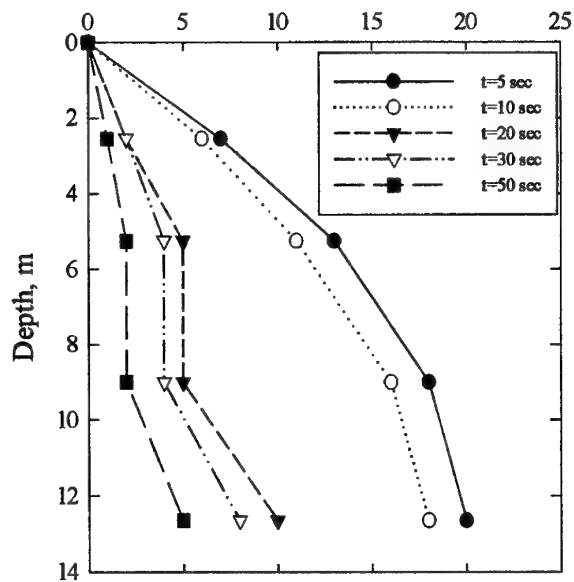
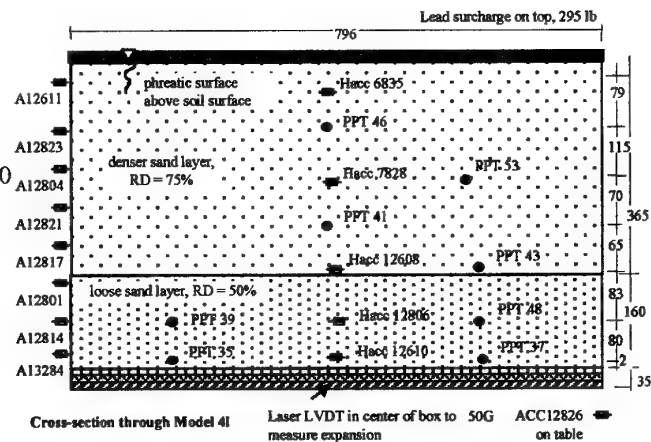**Model 2b Stress and strain isochrones**
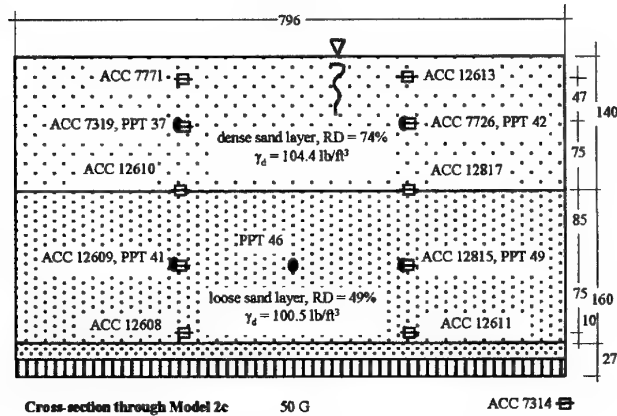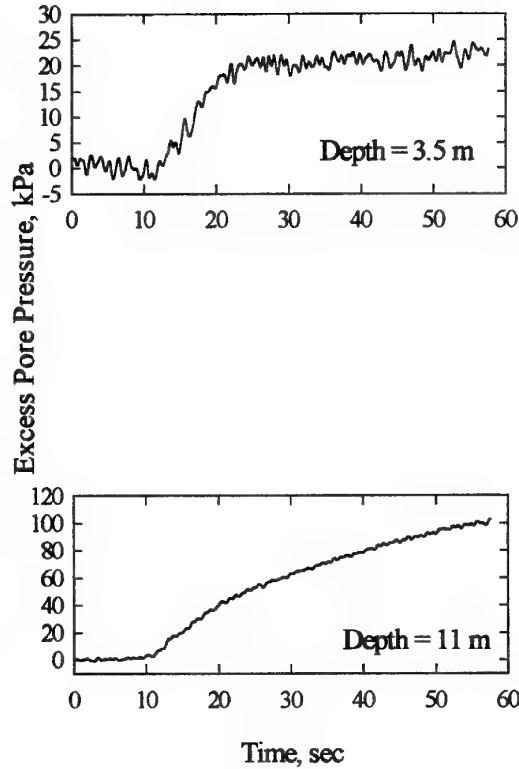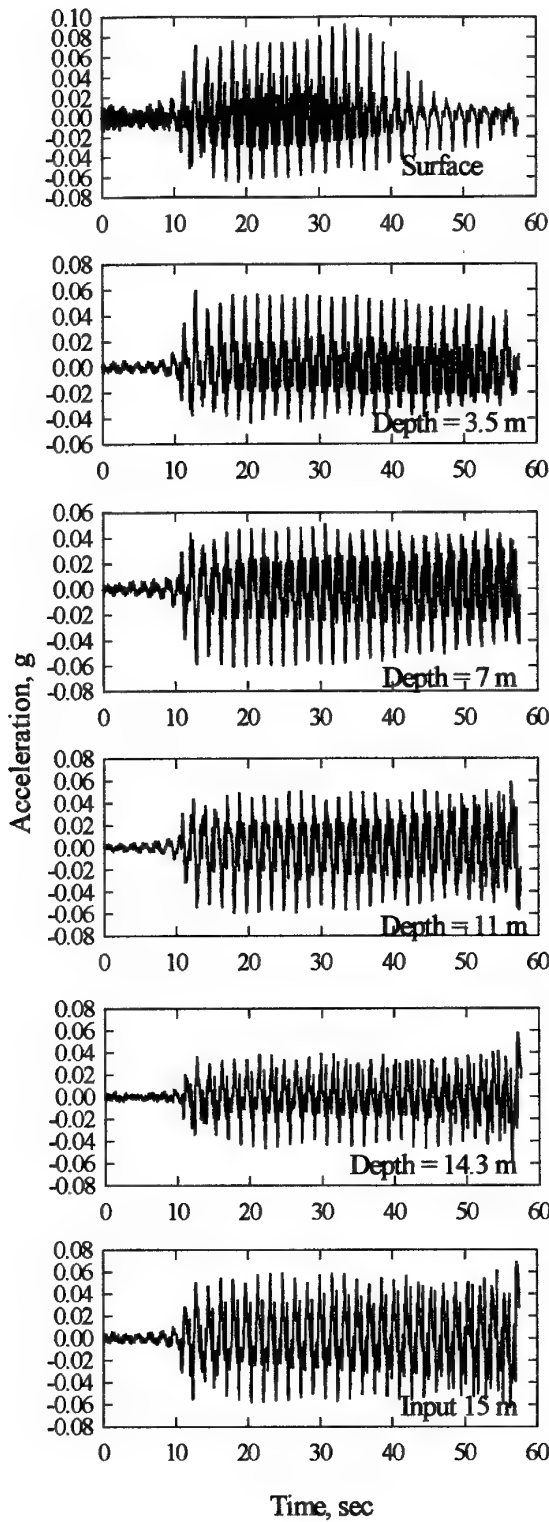
Model 2c
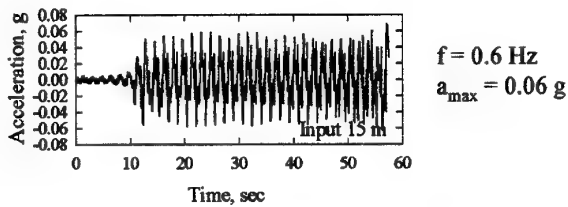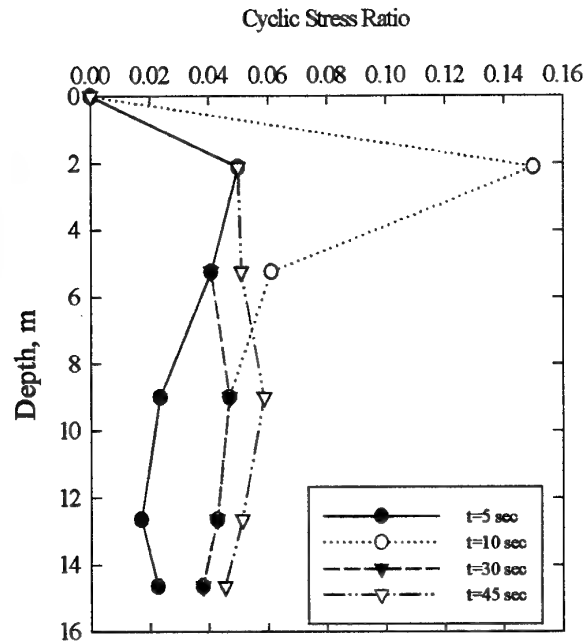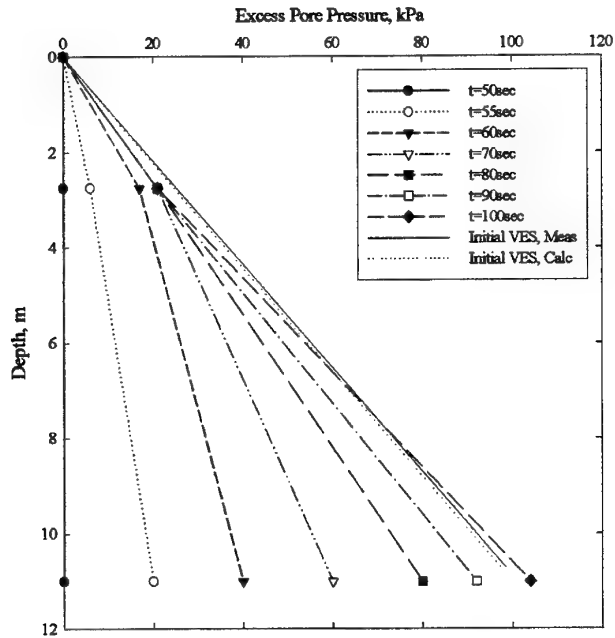
Model 2c-eq1

Model 2c-eq1

Model 2c-eq1
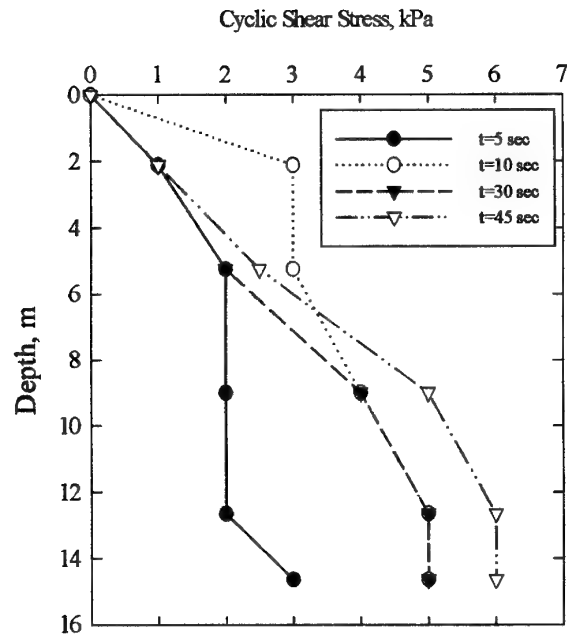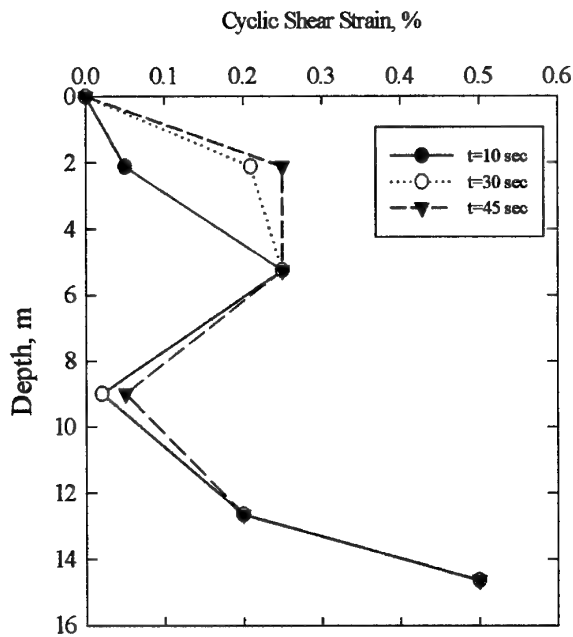
Model 2c Stress and strain isochrones

B-6

Model 2d

Model 2d-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

f = 0.6 Hz
a_{max} = 0.13 g

Input 15 m
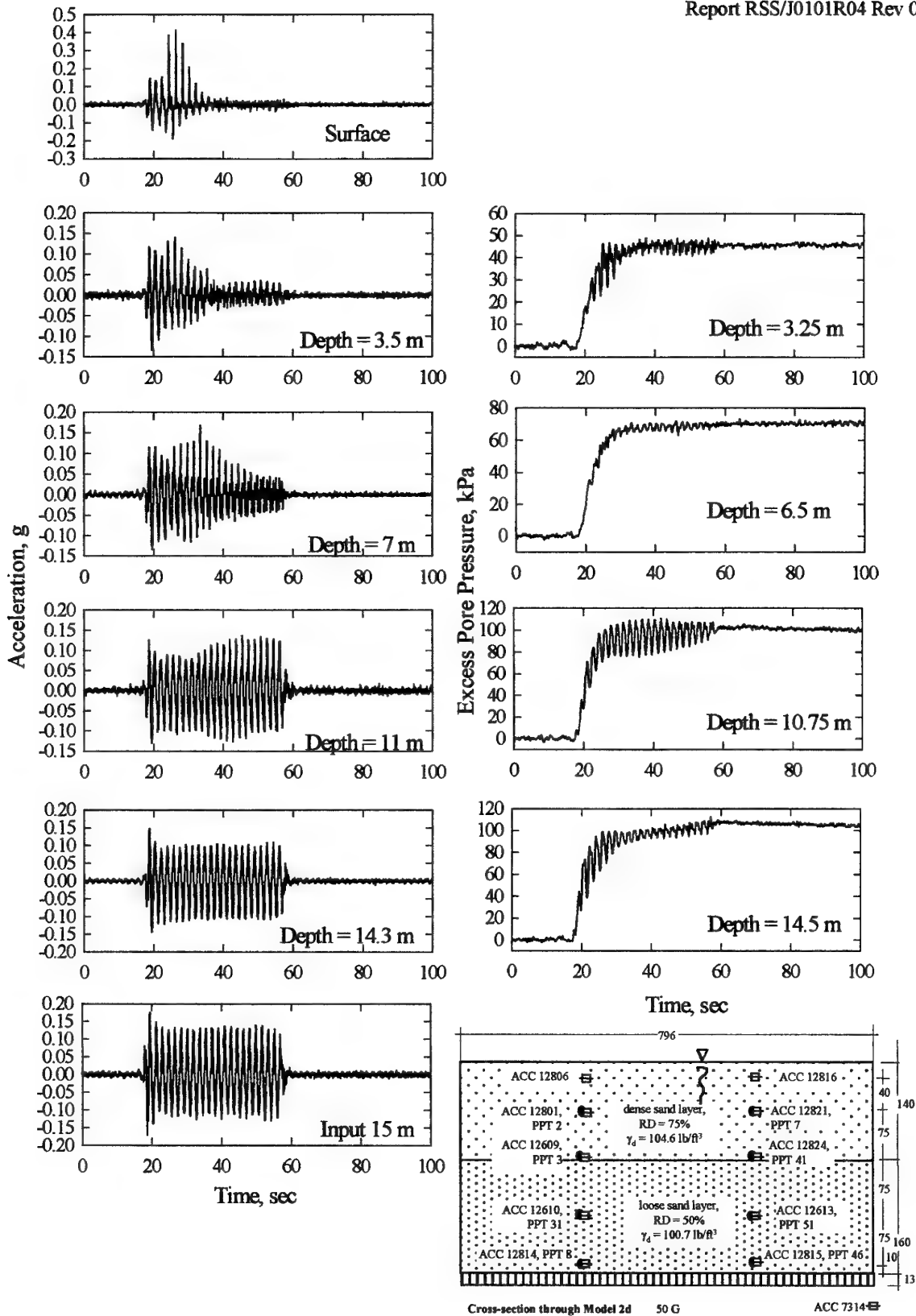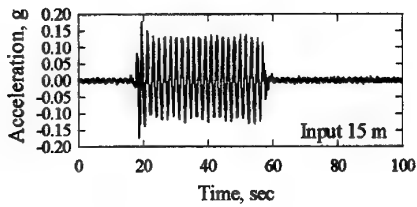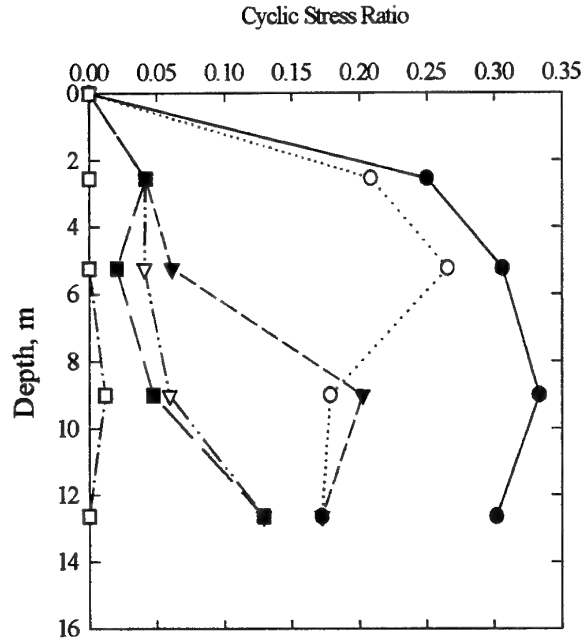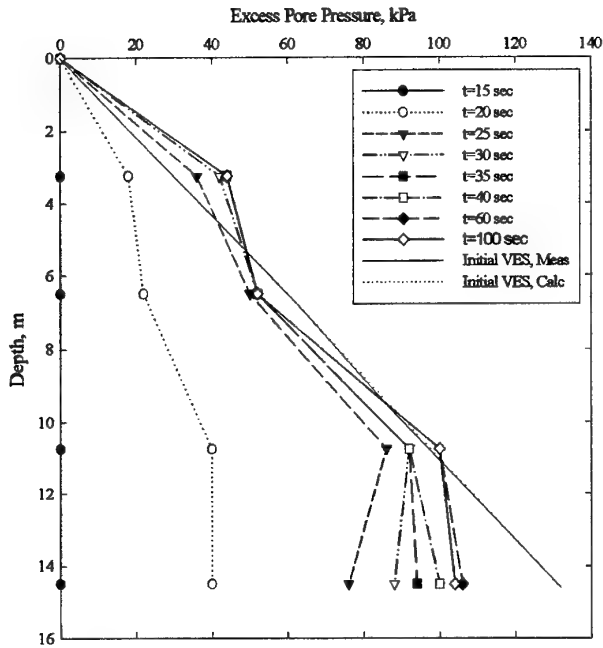
Model 2d-eq1

Cyclic Shear Strain, %
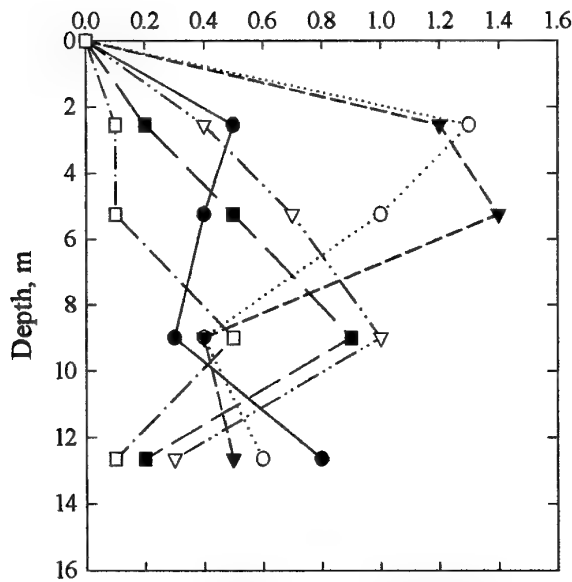
Model 2d-eq1

Cyclic Shear Stress, kPa
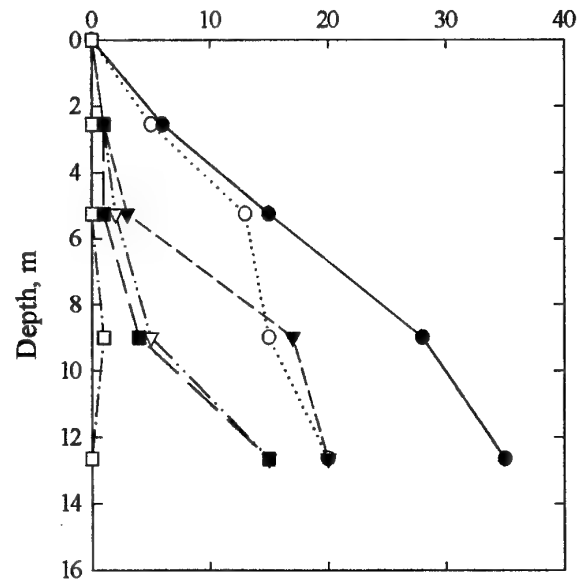
Model 2d Stress and strain isochrones

B-8

Cross-section through Model 2e   50 G

Model 2e

Model 2e-eq1

Excess Pore Pressure, kPa
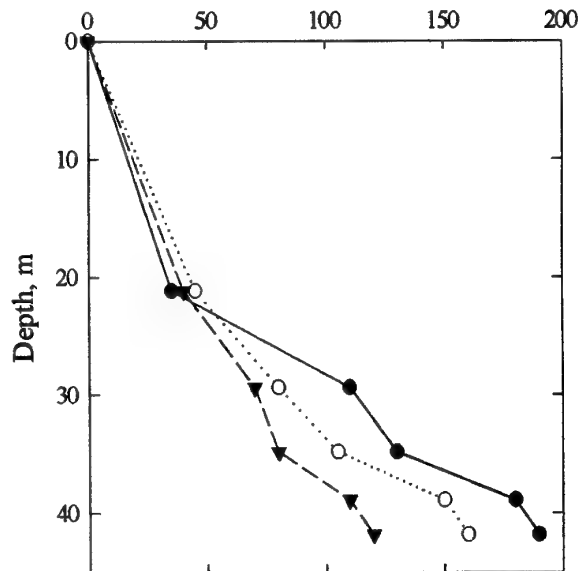
Cyclic Stress Ratio
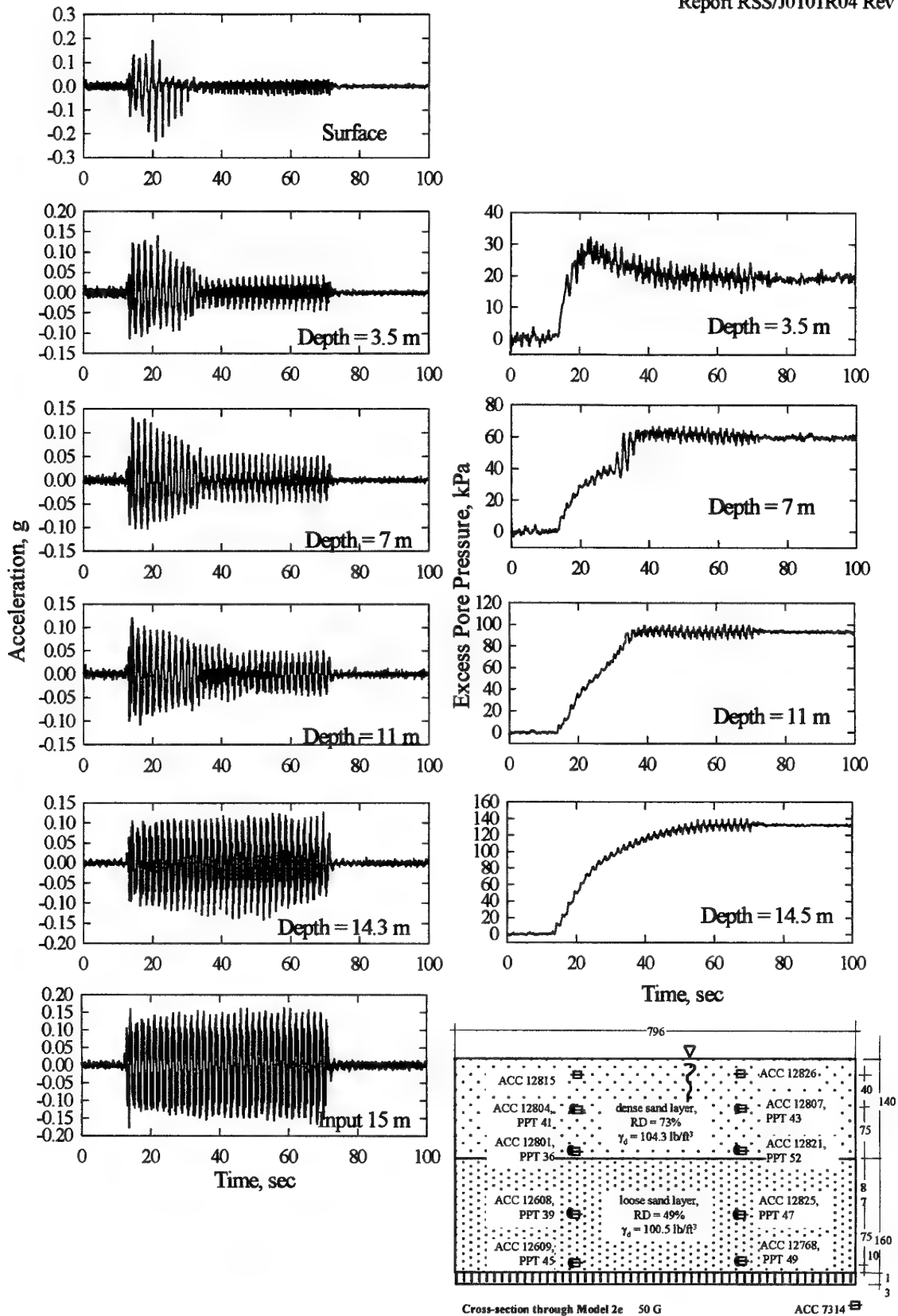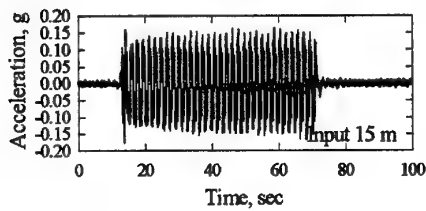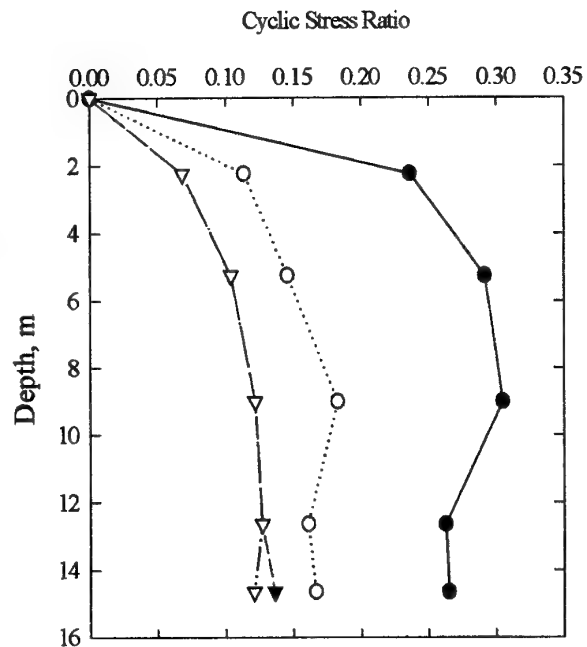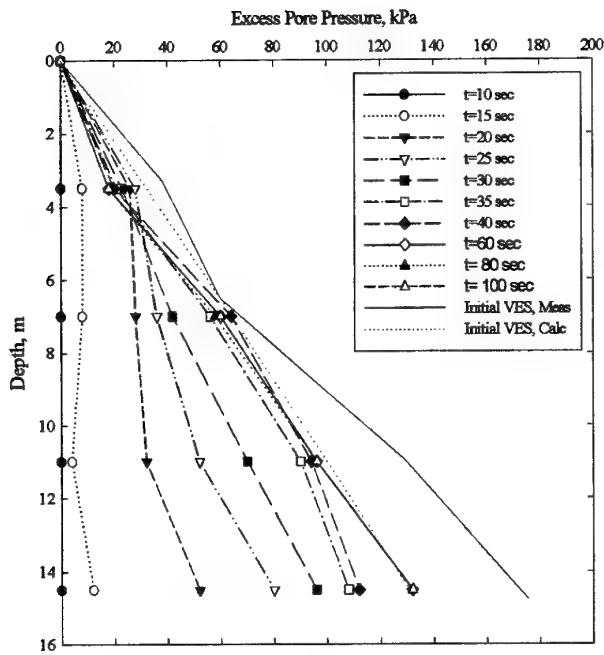
f = 0.6 Hz
a_{max} = 0.15 g

Model 2e-eq1

Cyclic Shear Strain, %
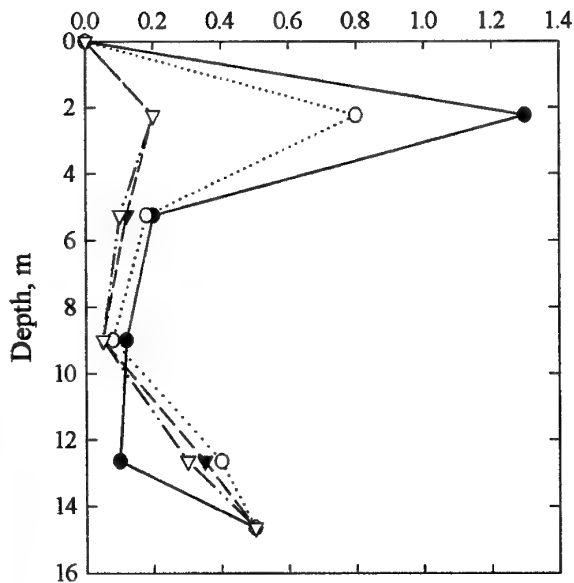
Model 2e-eq1

Cyclic Shear Stress, kPa
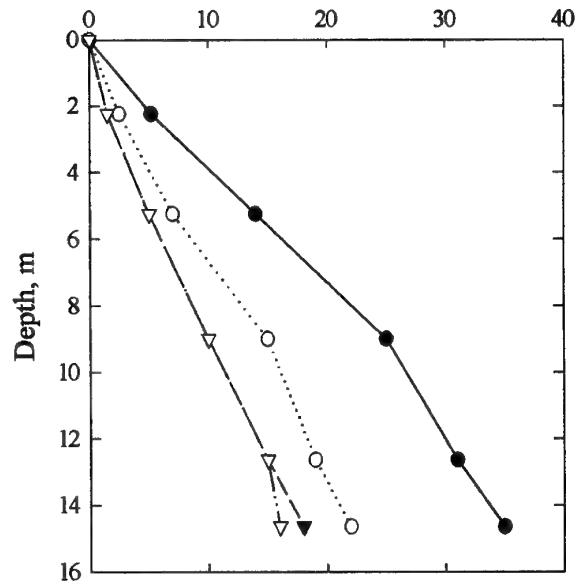
Model 2e Stress and strain isochrones

B-10

Acceleration, g

Depth = 1.5 m

Depth = 3.8 m

Depth = 6.5 m

Depth = 11.3 m

Depth = 14.5 m

Input, 15 m

Time, sec

Excess Pore Pressure, kPa

Depth = 3.5 m

Depth = 6.9 m

Depth = 11 m

Depth = 14.8 m

Time, sec

796

ACC 12768   ACC 12804

ACC 12608,
PPT 38   ACC 12801,
PPT 51

ACC 12806,
PPT 15   dense sand layer, RD = 75%
γ_d = 104.5 lb/ft³   ACC 12821,
PPT 31

45
140
65

ACC 12609, PPT 47   ACC 12808, PPT 50

loose sand layer, RD = 50%
γ_d = 100.7 lb/ft³

85

ACC 12811, PPT 41   ACC 12815, PPT 46

75   160
10
13

Cross-section through Model 2f   50 G   ACC 7314

Model 2f

B-11

Model 2f-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

f = 0.6 Hz
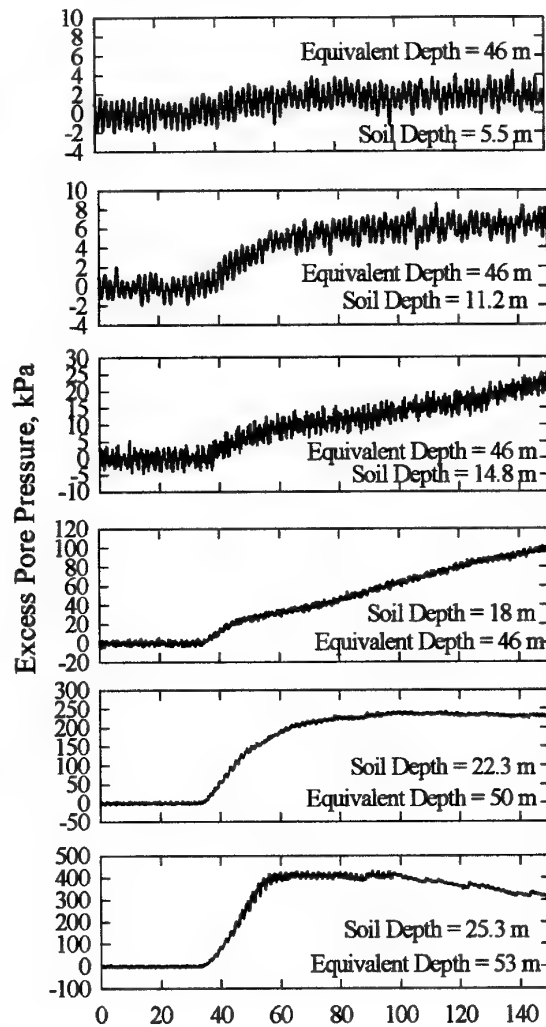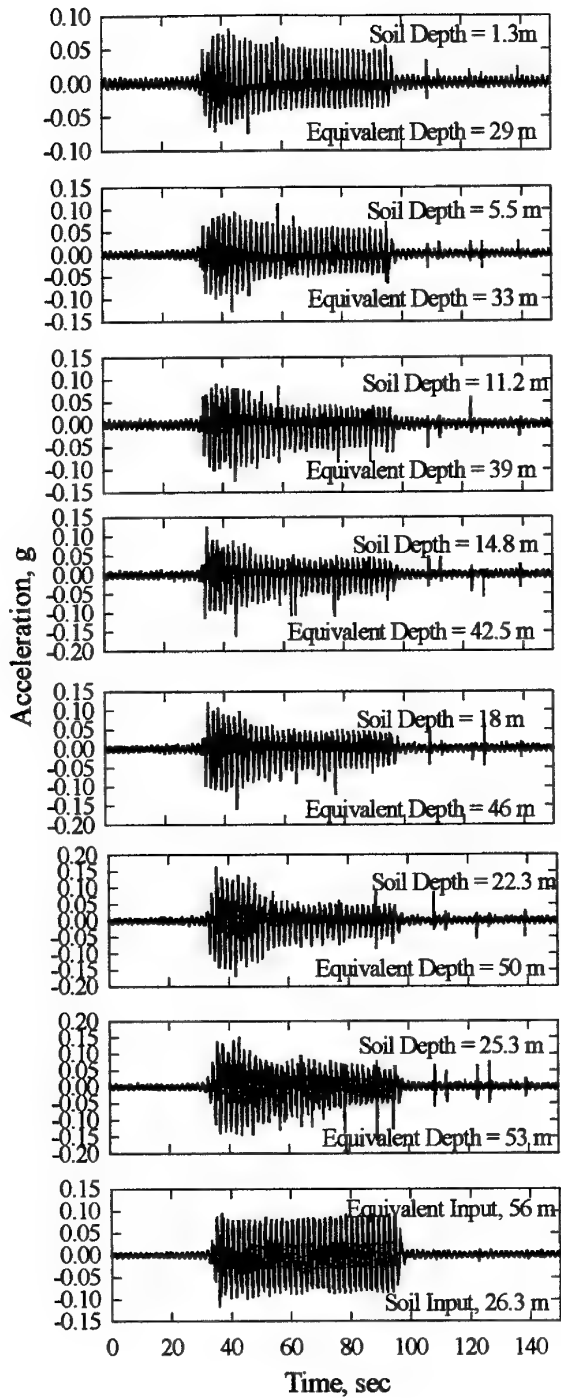a_max = 0.2 g

$f = 0.6$ Hz
$a_{max} = 0.2$ g

Model 2f-eq1

Cyclic Shear Strain, %
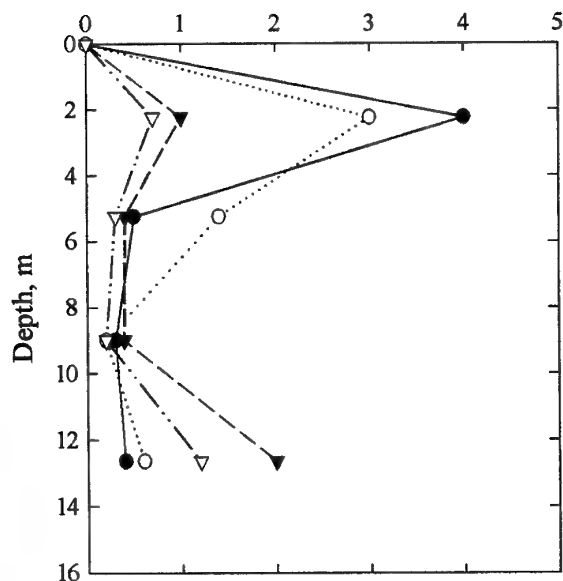
Model 2f-eq1

Cyclic Shear Stress, kPa
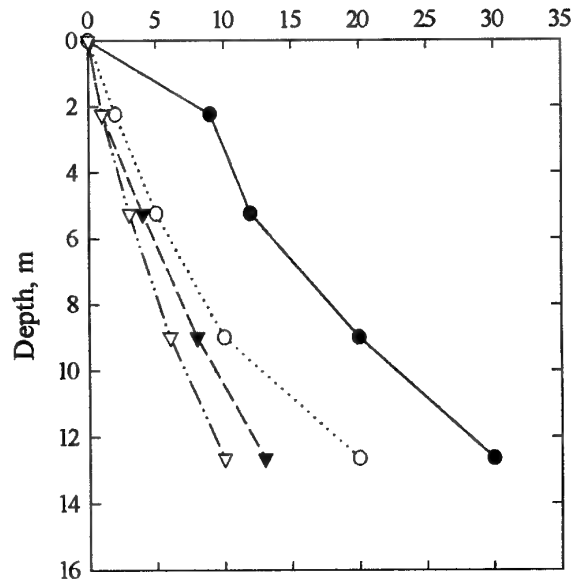
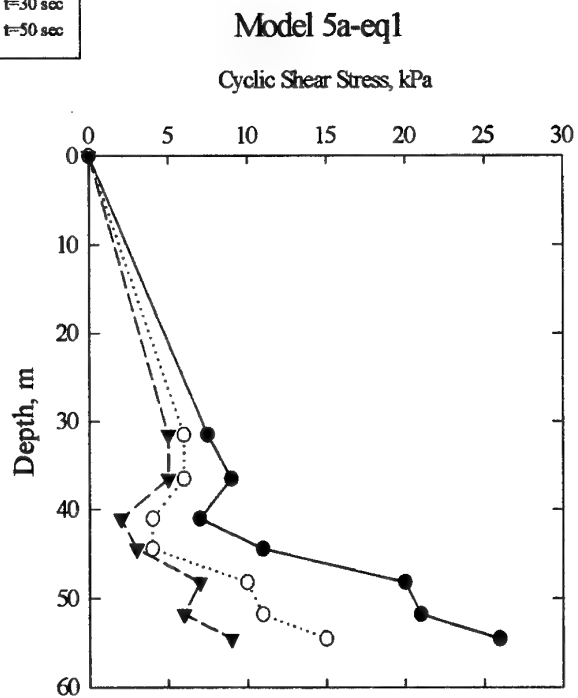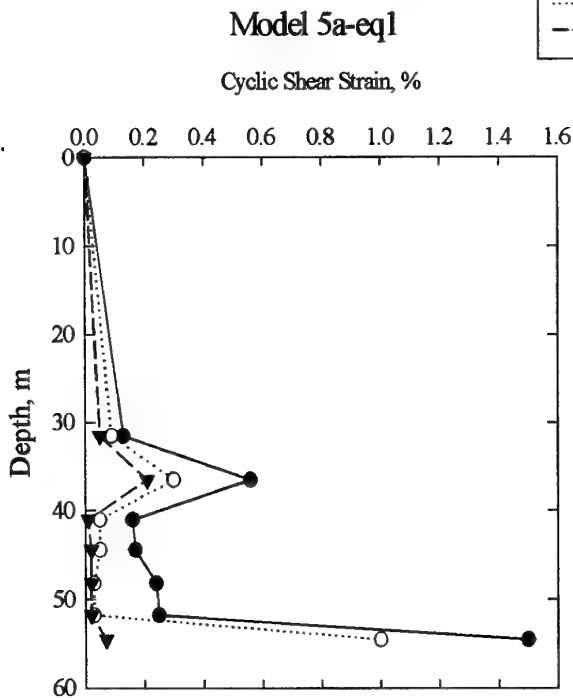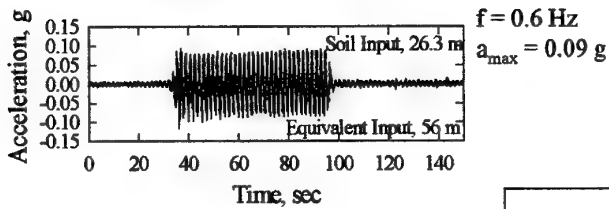**Model 2f Stress and strain isochrones**

B-12

Surface

Depth = 5.75 m

Depth = 14.75 m

Depth = 14.75 m

Depth = 18.25 m

Depth = 22.5 m

Depth = 22.5 m

Depth = 26 m

Acceleration, g

Excess Pore Pressure, kPa

Time, sec

Time, sec

796

ACC 12612   ACC 12613

ACC 12610   denser sand layer,   ACC 12611
              RD = 73%
              γ_d = 104.3 lb/ft³

ACC 5754   ACC 3457

ACC 6835   PPT 31   ACC 7709

ACC 7319   ACC 7706

ACC 7771,   loose sand layer,   ACC 7828, PPT 9
PPT 10   RD = 34%
             γ_d = 98.4 lb/ft³

ACC 7318   ACC 7726

Cross-section through Model 3a   50 G   ACC 7314

100

105   365

75

70

85   160

70

10

35

B-13   Model 3a

Model 3a-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

	t=10 sec
	t=15 sec
	t=20 sec
	t=25 sec
	t=30 sec
	t=40 sec
	t=60 sec
	t=100 sec
	t=150 sec
	Initial VES, Meas
	Initial VES, Calc

Note: PPT at 15m appears to have stopped
responding at 15 seconds, or 10 seconds into shake

f = 0.6 Hz
a_{max} = 0.2 g

Depth = 26 m

Time, sec

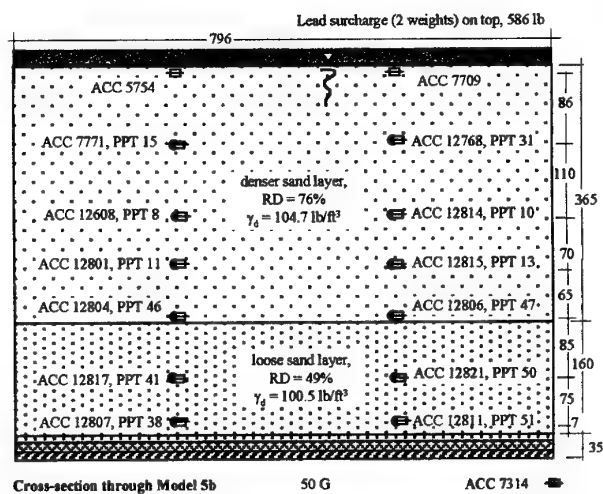| | t=10 sec |
	t=20 sec
	t=40 sec
	t=60 sec

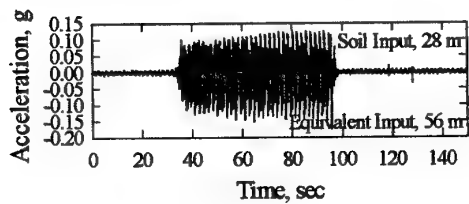Model 3a-eq1

Cyclic Shear Strain, %

Model 3a-eq1

Cyclic Shear Stress, kPa
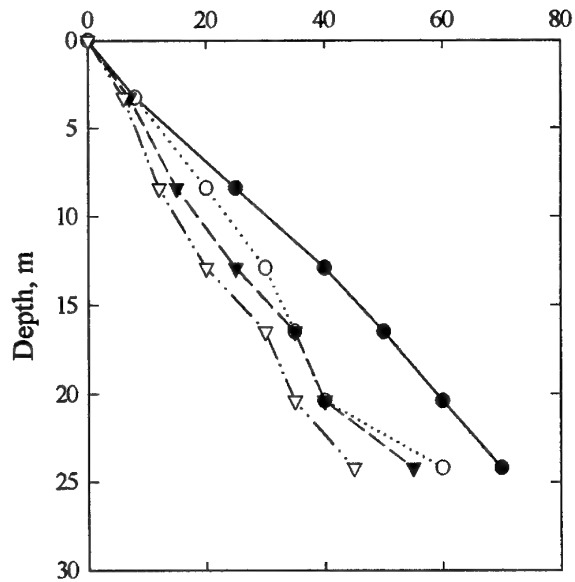
Model 3a Stress and strain isochrones

B-14

Model 3b

Cross-section through Model 3b   50 G   ACC 7314

B-15

Model 3b-eq2

Excess Pore Pressure, kPa

Cyclic Stress Ratio

f = 0.6 Hz
a_{max} = 0.07 g

Input, 26 m

Note: PPT's did not record during
EQ #1, using EQ #2 data

Legend (top plot):
- t=5 sec
- t=10
- t=15
- t=20
- t=25
- t=30
- t=35
- t=40
- t=60
- t=80
- t=100
- Initial VES, Meas
- Initial VES, Calc

Legend (bottom plots):
- t=10 sec
- t=20 sec
- t=40 sec
- t=60 sec
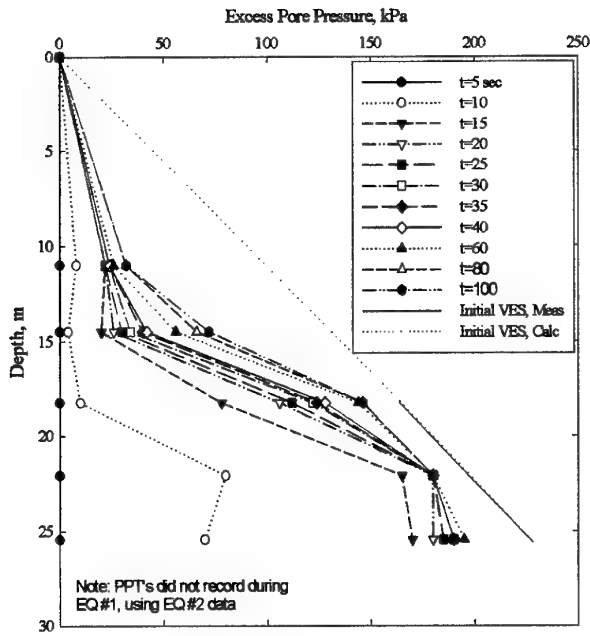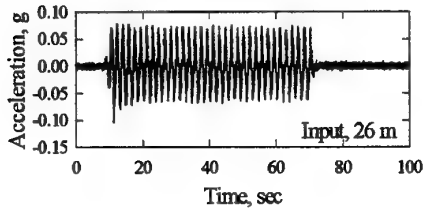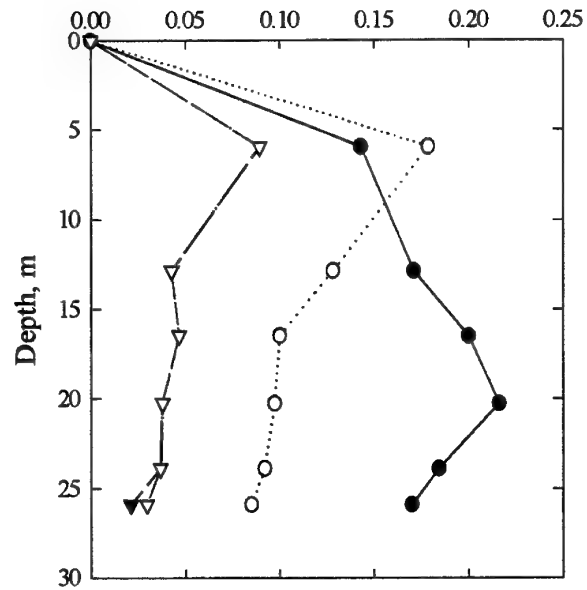
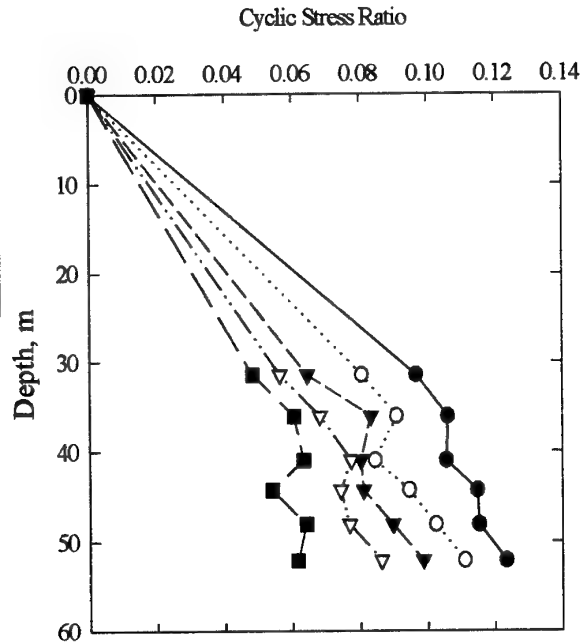## Model 3b-eq1

Cyclic Shear Strain, %
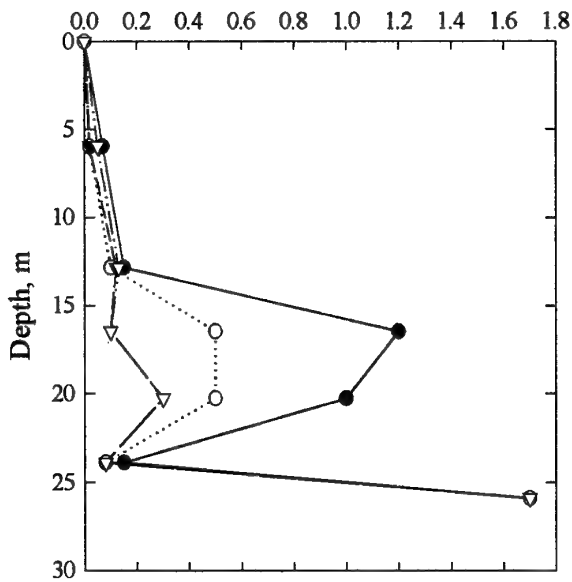
Model 3b-eq1

Cyclic Shear Stress, kPa
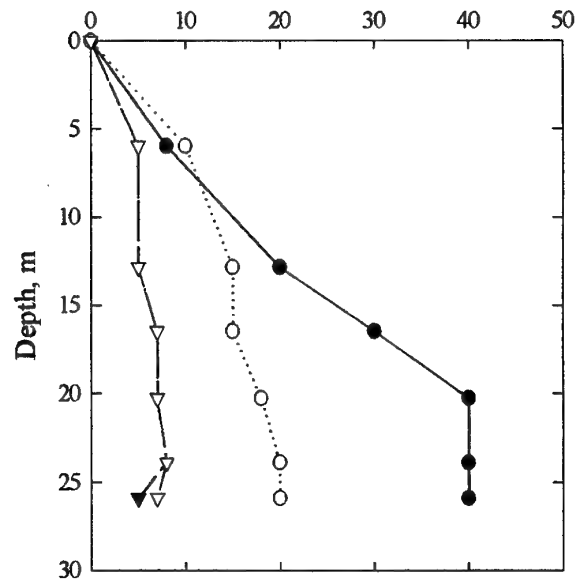
Model 3b Stress and strain isochrones

Model 3c

B-17

Model 3c-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

Legend:
- t=5 sec
- t=10 sec
- t=15 sec
- t=20 sec
- t=25 sec
- t=30 sec
- t=40 sec
- t=60 sec
- t=100 sec
- Initial VES, Meas
- Initial VES, Calc

f = 0.6 Hz
a_{max} = 0.07 g

Input, 27 m

Legend:
- t=10 sec
- t=20 sec
- t=40 sec
- t=60 sec
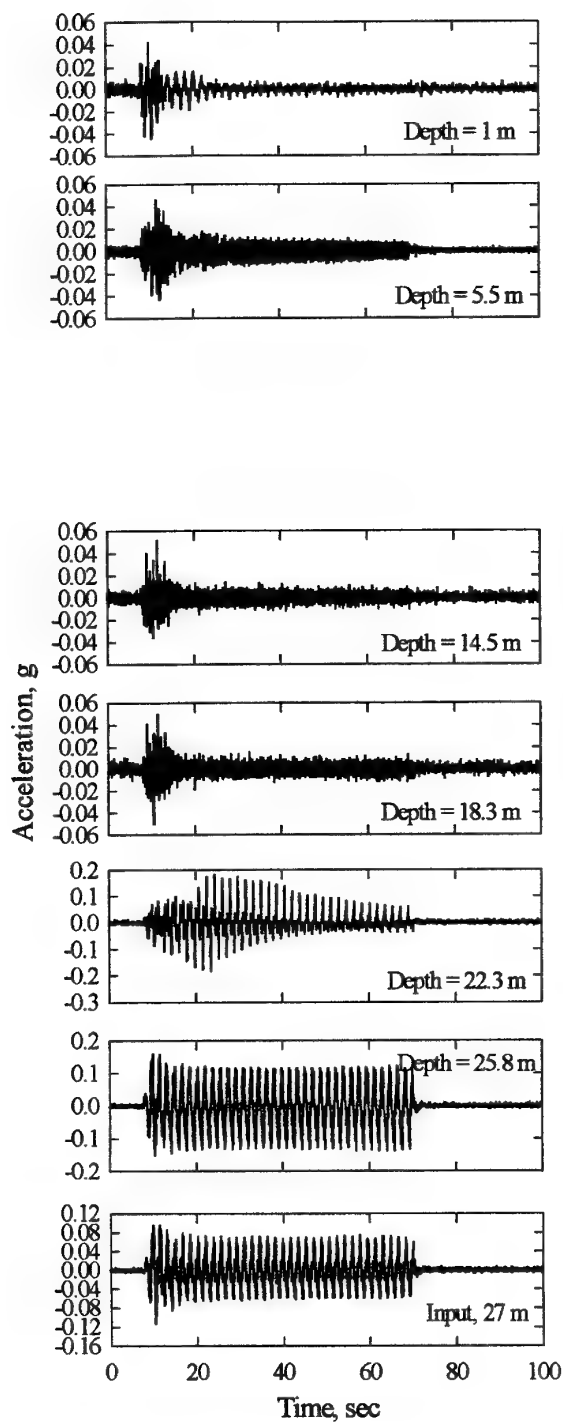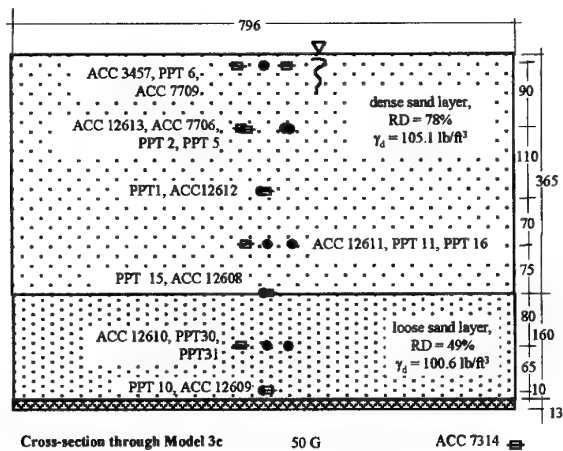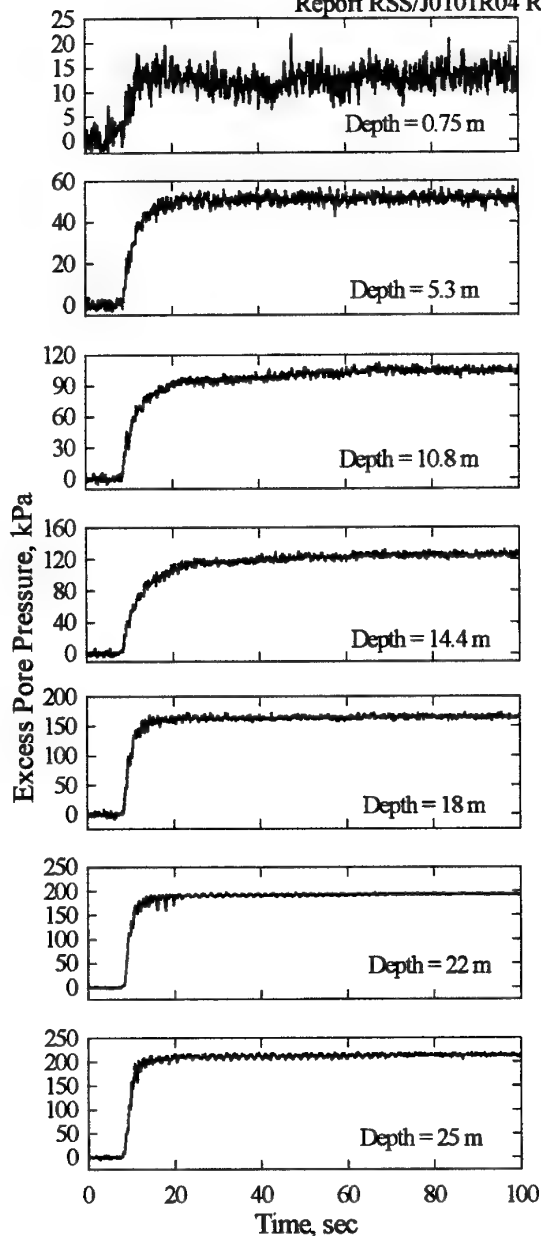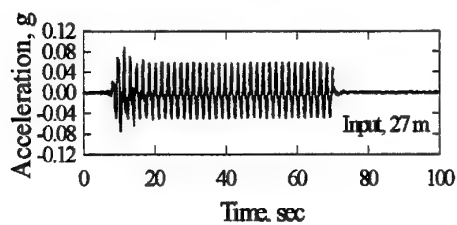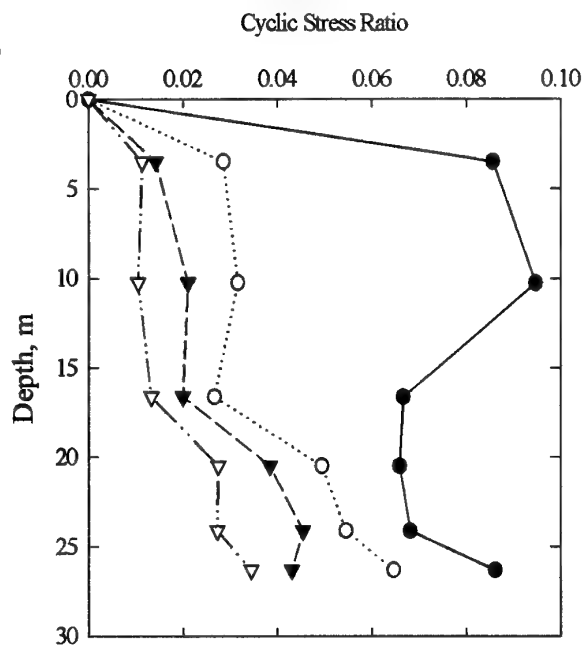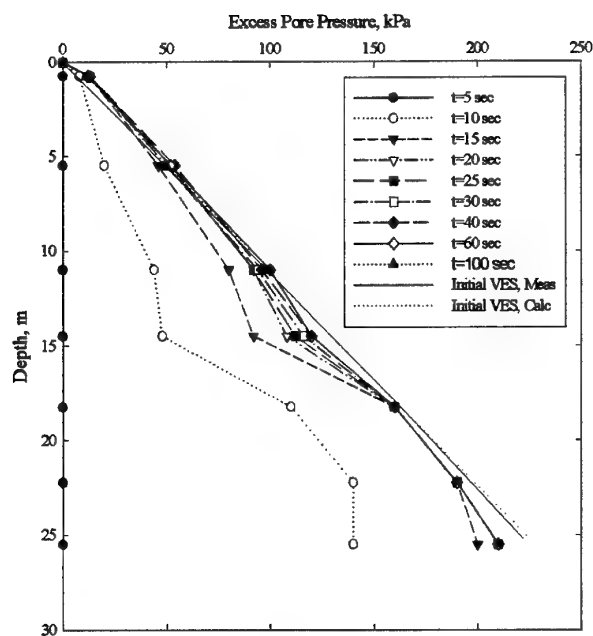
Model 3c-eq1

Cyclic Shear Strain, %
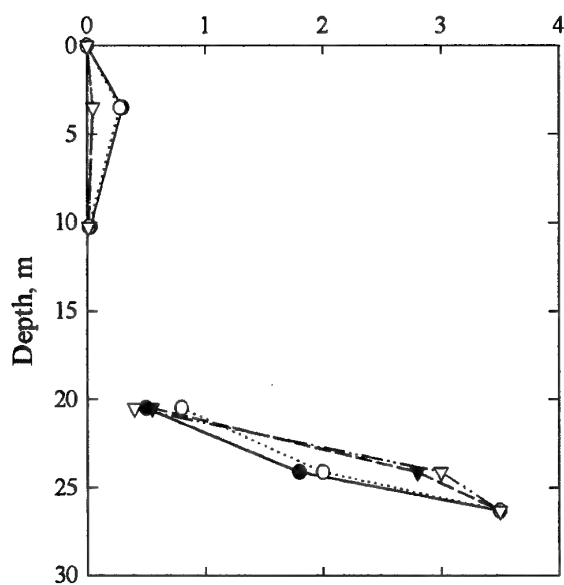
Model 3c-eq1

Cyclic Shear Stress, kPa
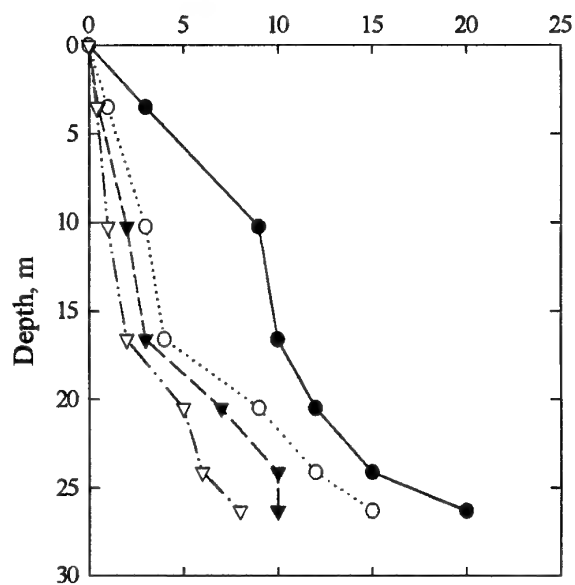
Model 3c Stress and strain isochrones

B-18

Cross-section through Model 3d

Model 3d

B-19

Model 3d-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio
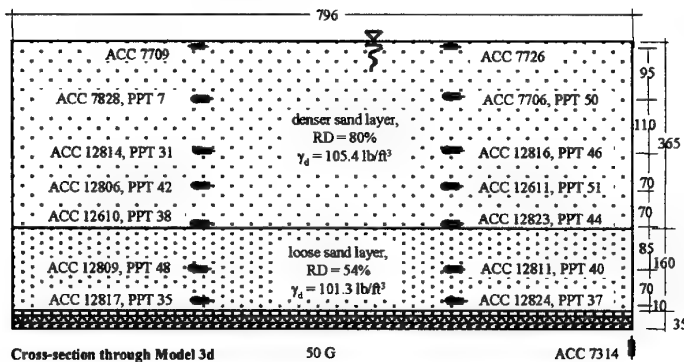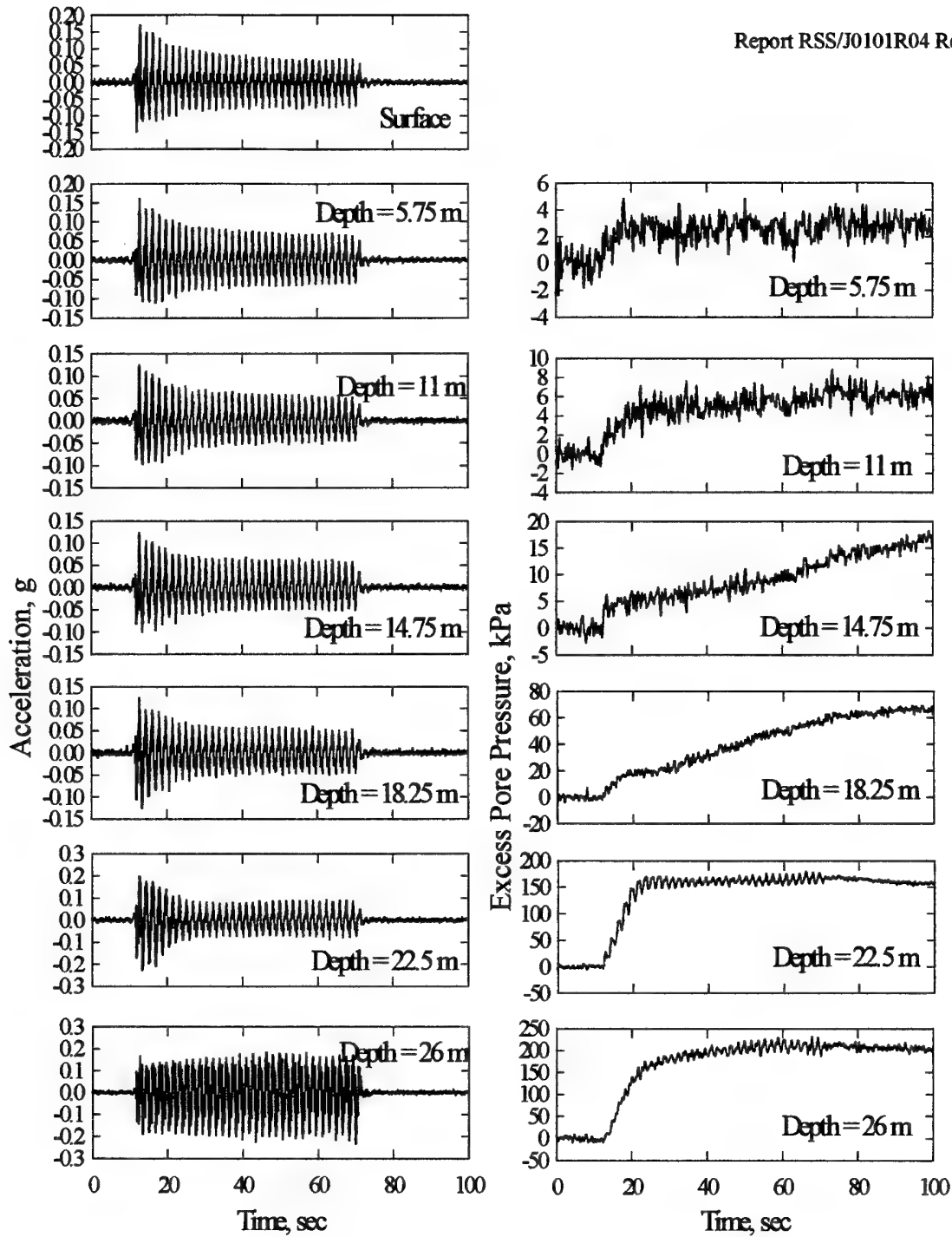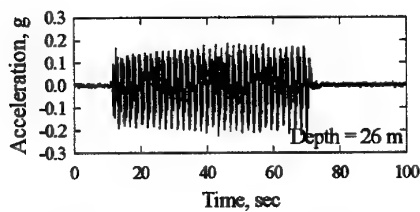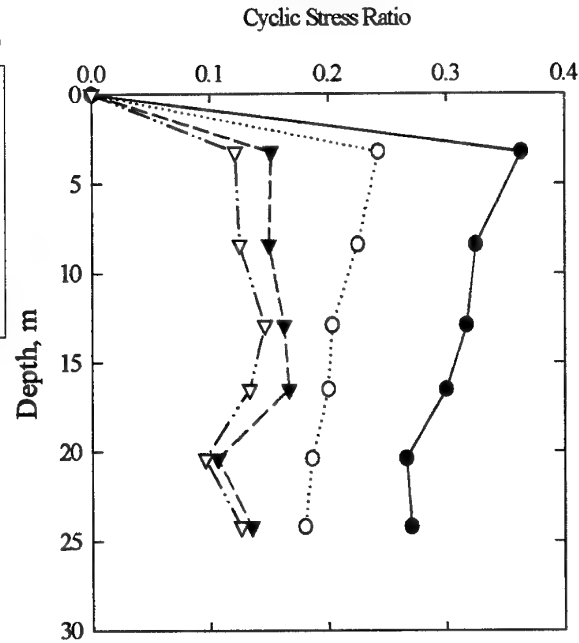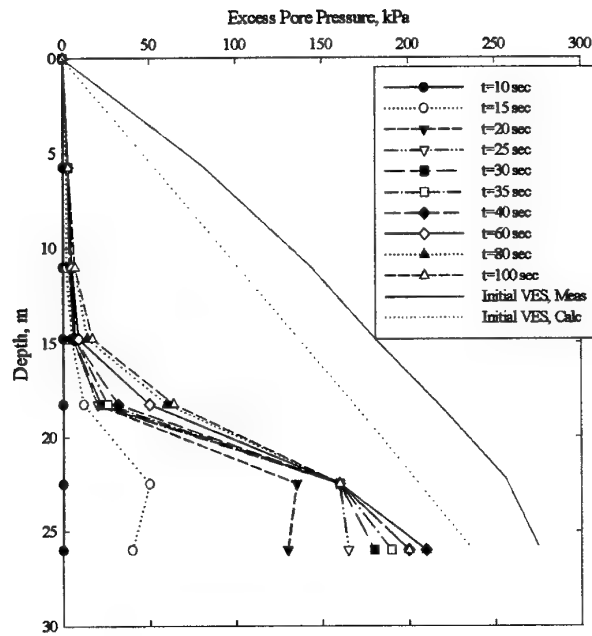
f = 0.6 Hz
a_max = 0.19 g

Model 3d-eq1

Cyclic Shear Strain, %

Model 3d-eq1

Cyclic Shear Stress, kPa

Model 3d Stress and strain isochrones

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Model 3e

B-21

Model 3e   Test at 50 G
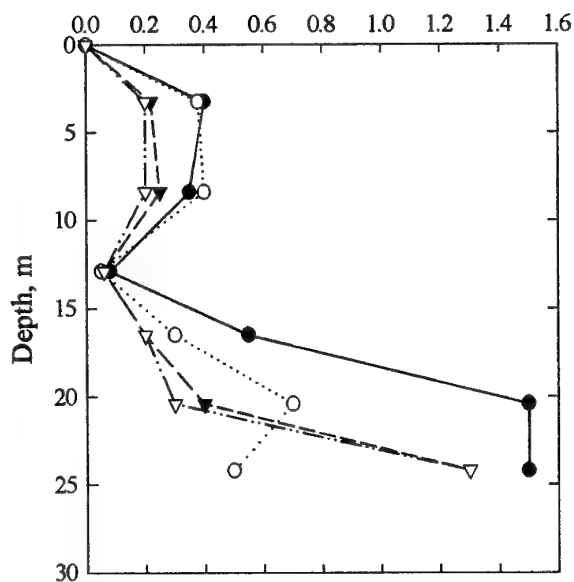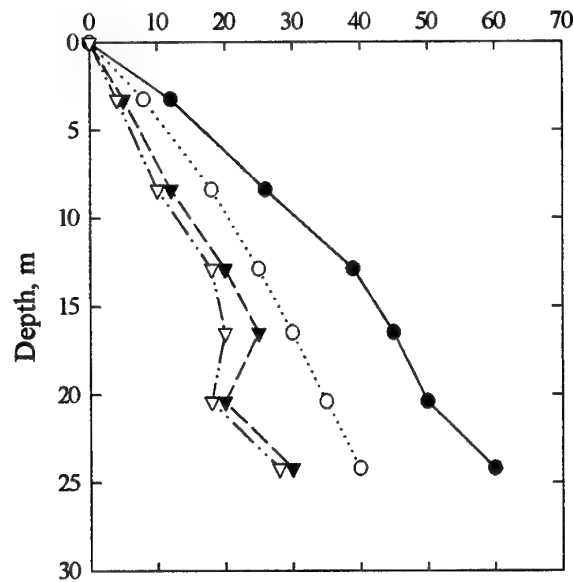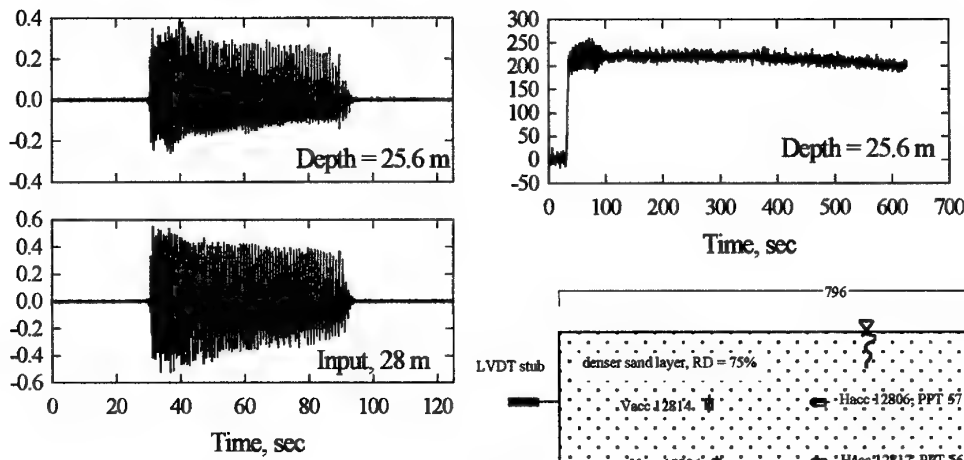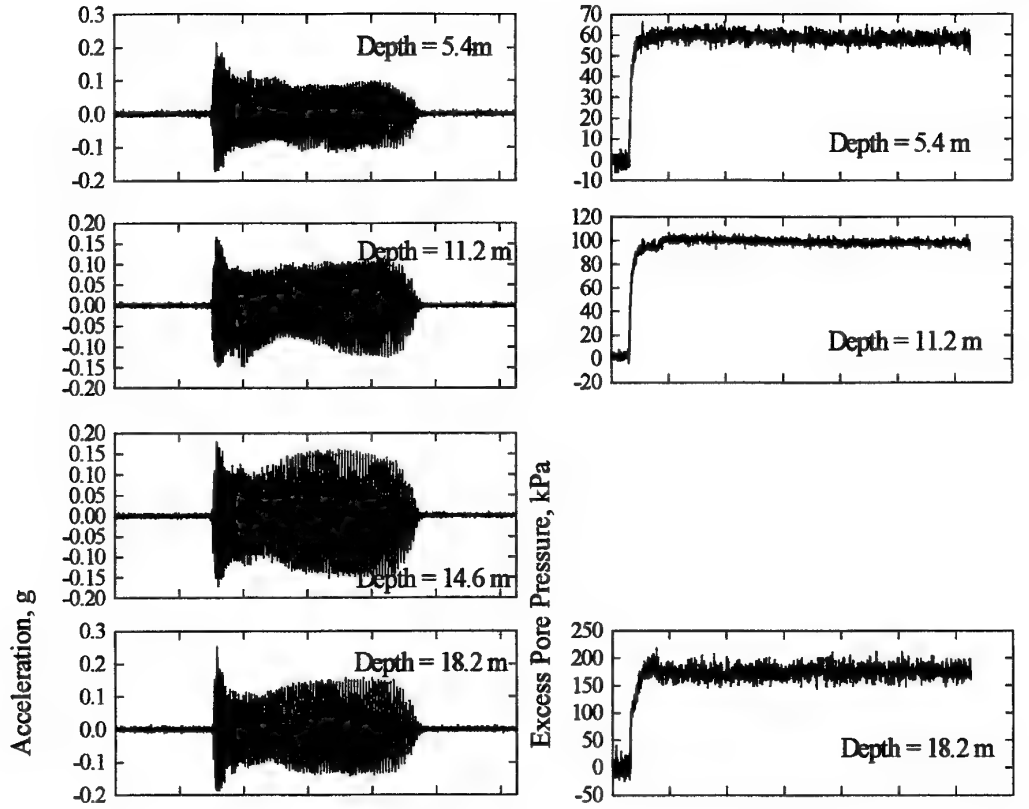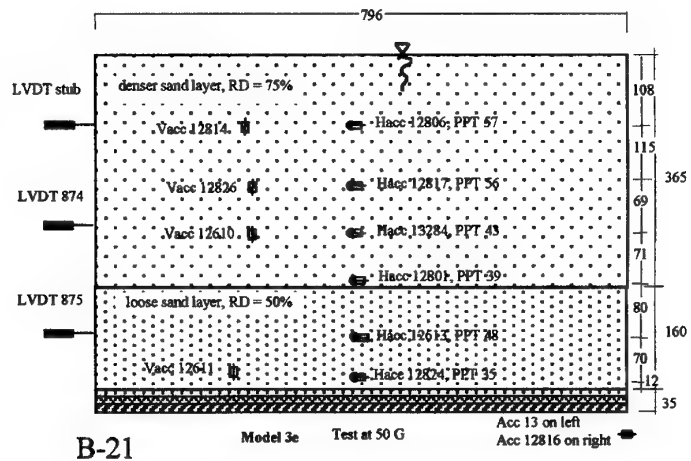
Model 3e (Archtest 2a, no weight)

Excess Pore Pressure, kPa

Cyclic Stress Ratio

f = 1.2 Hz
a_{max} = 0.4 g

Input, 28 m
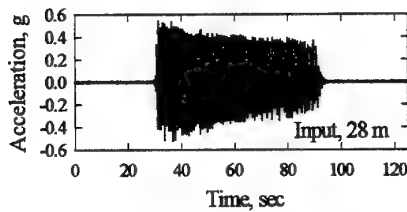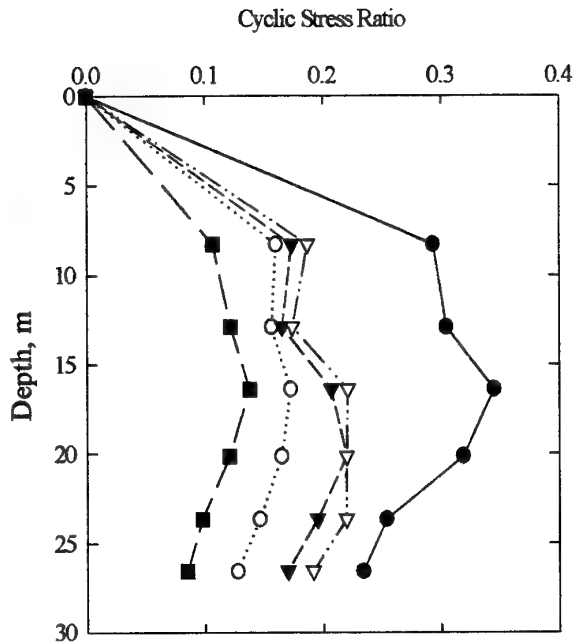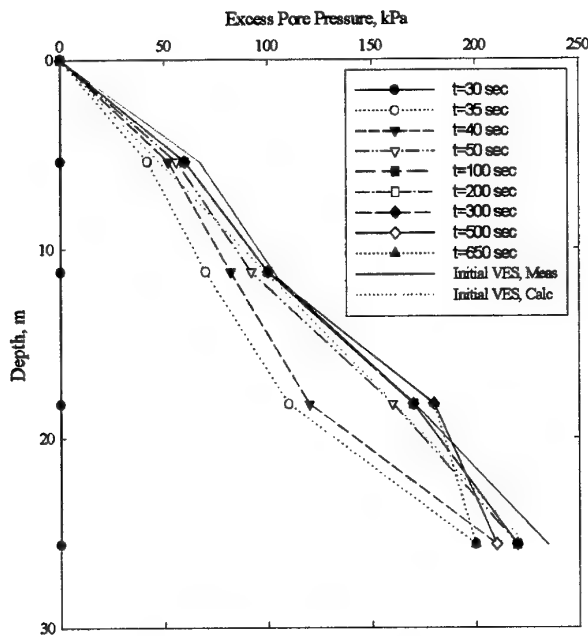
Model 3e-eq1

Cyclic Shear Strain, %
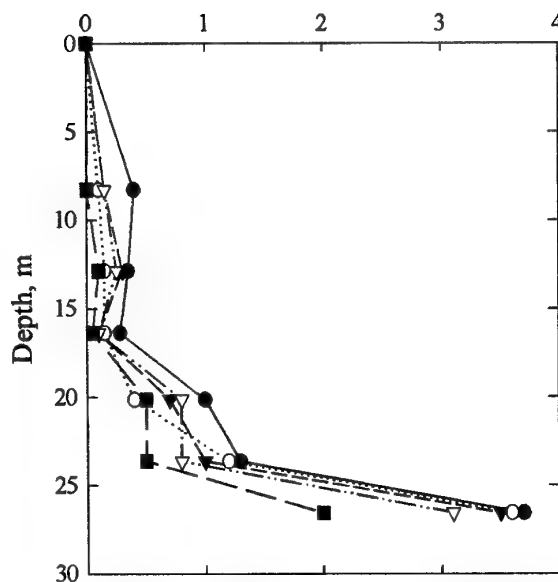
Model 3e-eq1

Cyclic Shear Stress, kPa
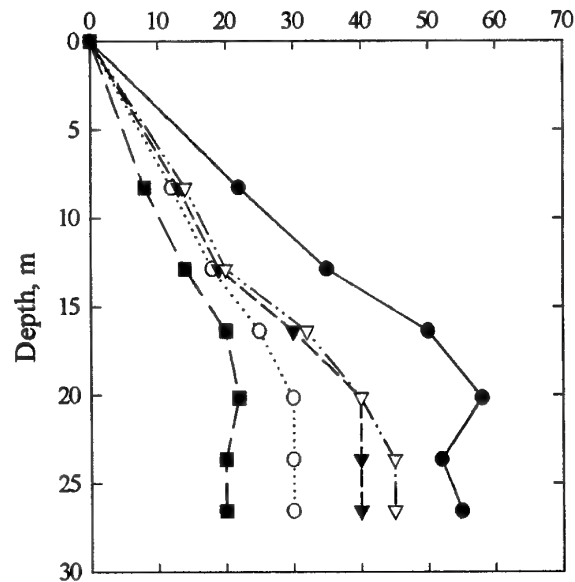
Model 3e Stress and strain isochrones

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Model 3f

Model 3f (Half Scale 100g)

Report RSS/J0101R04 Rev 0

Cyclic Stress Ratio

Excess Pore Pressure, kPa

Legend:
- t=37.5sec
- t=43.75sec
- t=50sec
- t=75sec
- t=100sec
- t=150 sec
- t=200 sec
- t=400 sec
- t=800 sec
- t=1200 sec
- t=1500 sec
- Initial VES, Meas
- Initial VES, Calc

Input, 28 m
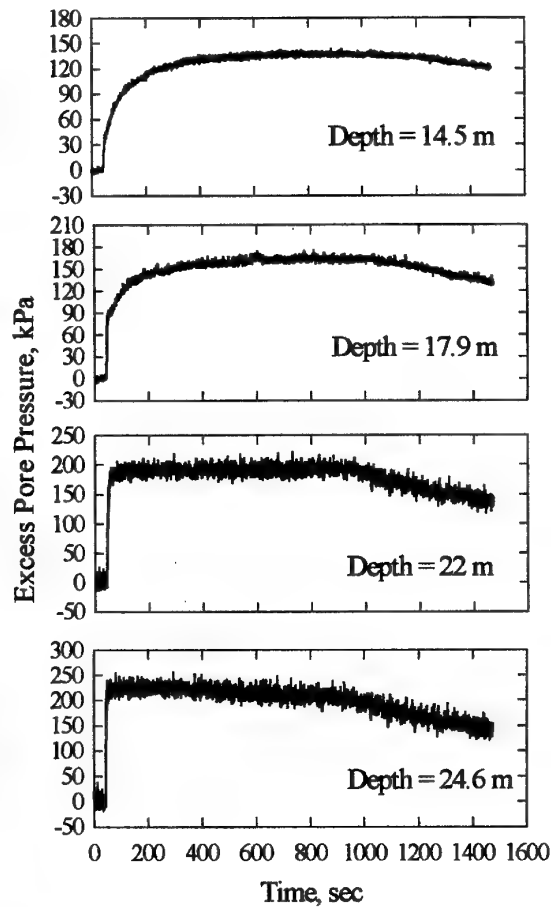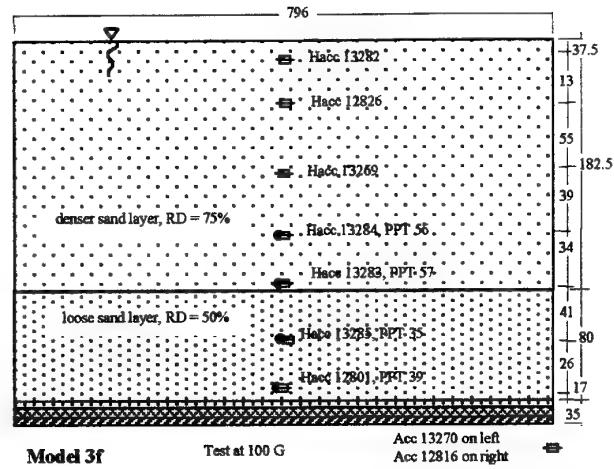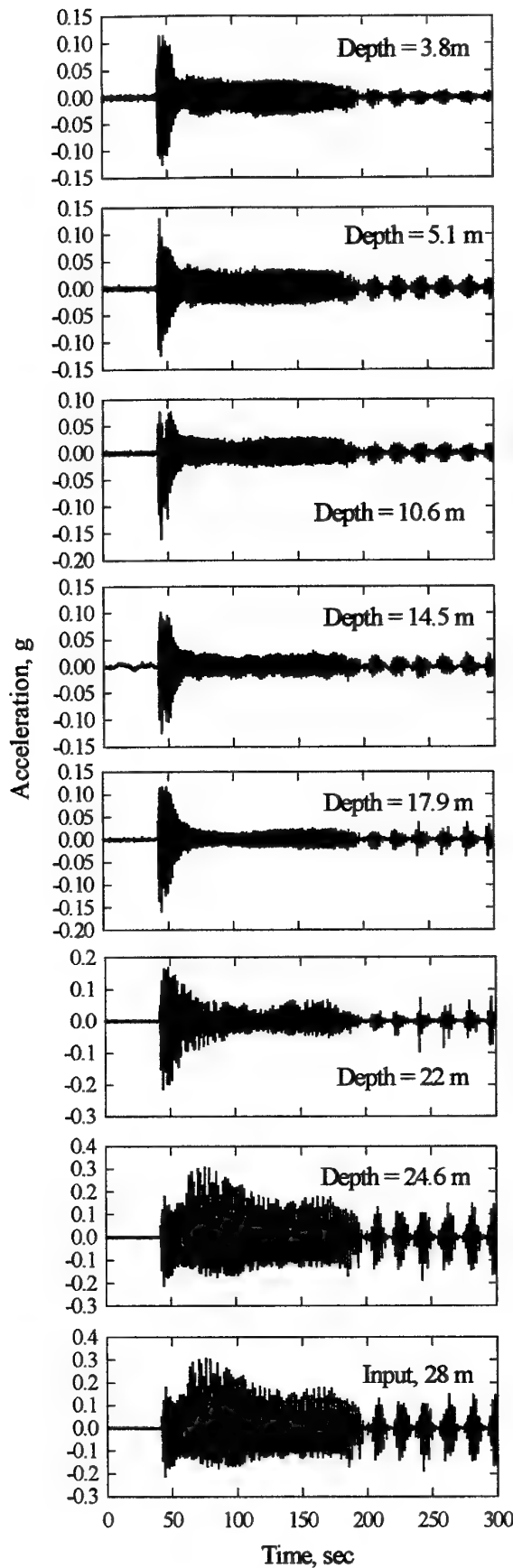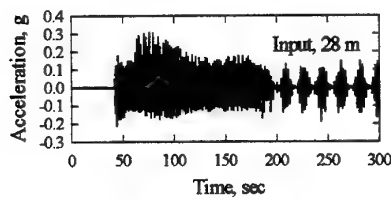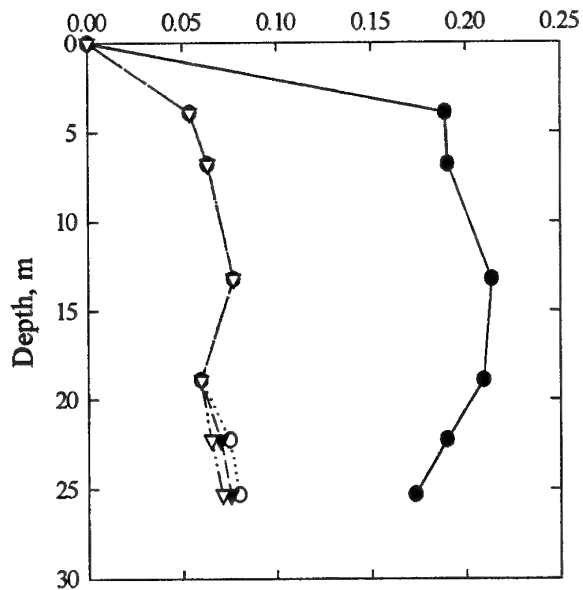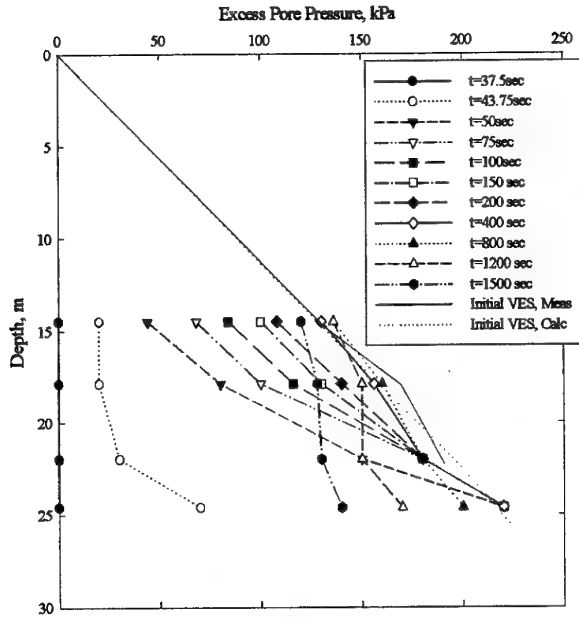
$f = 0.6$ Hz
$a_{max} = 0.2$ g

Model 3f-eq1

Cyclic Shear Strain, %

Legend:
- t=25 sec
- t=50 sec
- t=100 sec
- t=150 sec
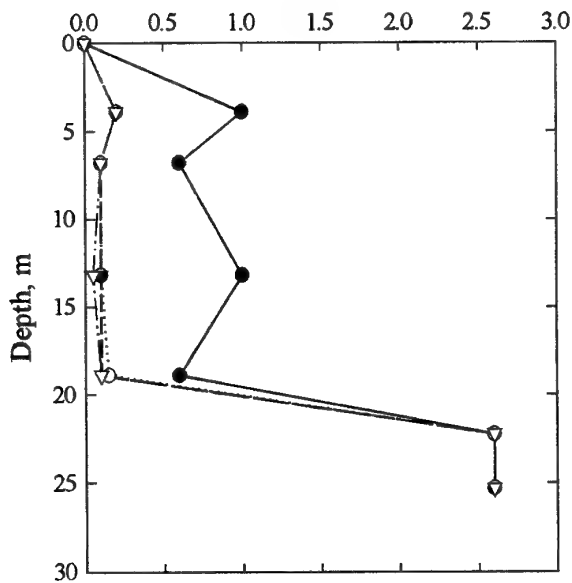
Model 3f-eq1

Cyclic Shear Stress, kPa
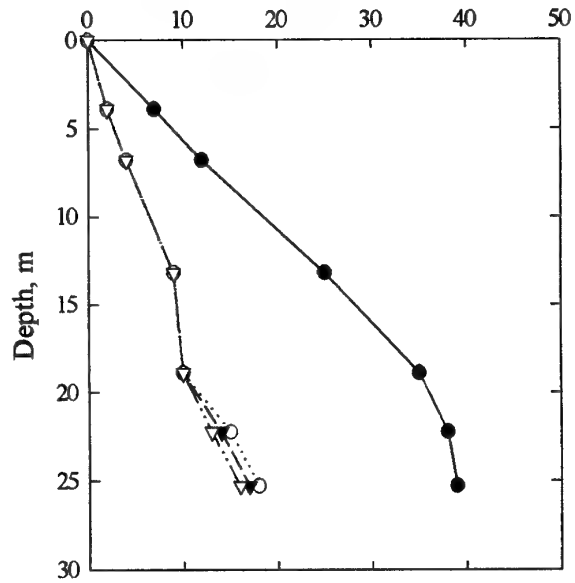
Model 3f Stress and strain isochrones

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Cross-section through Model 4a
Saturated loose layer, dense layer not saturated

Model 4a

Excess Pore Pressure, kPa

Cyclic Stress Ratio

f = 0.6 Hz
a_{max} = 0.09 g

Depth = 26 m
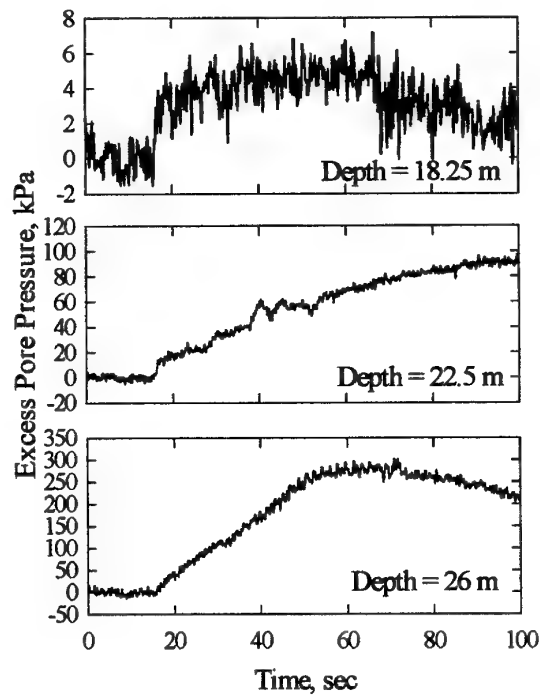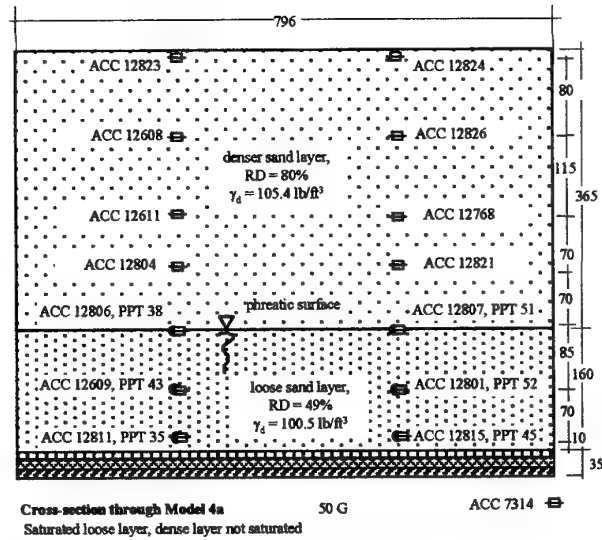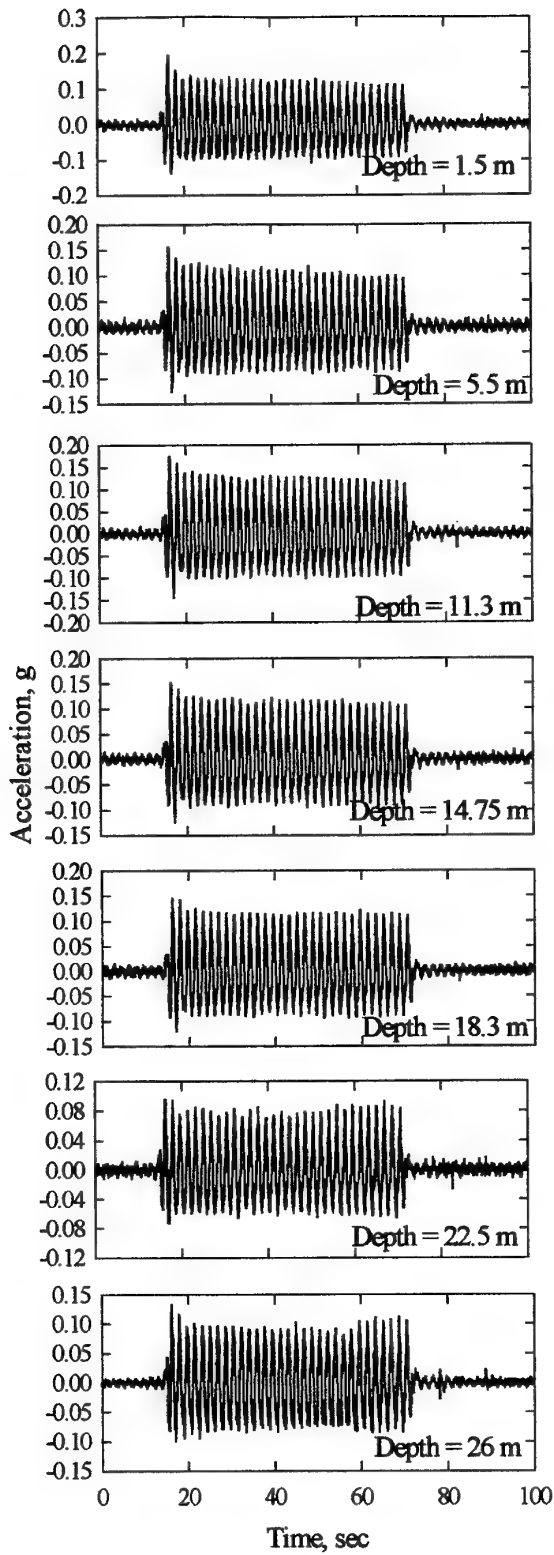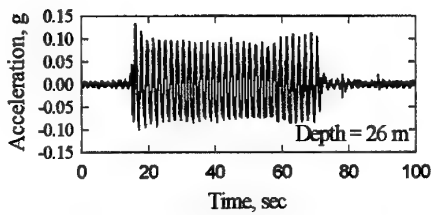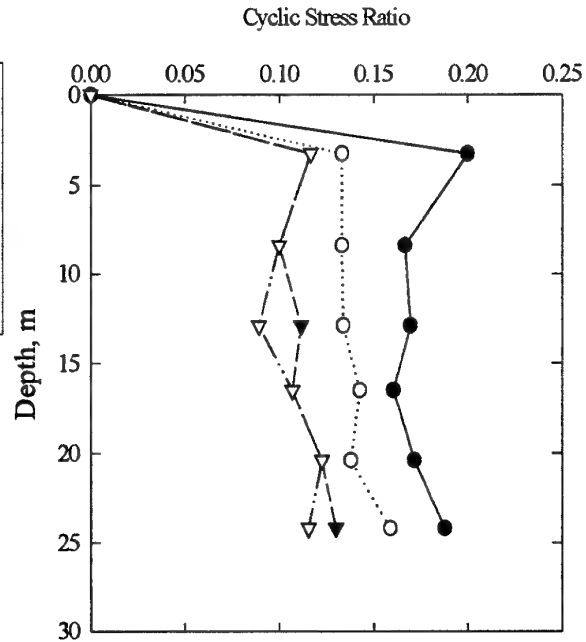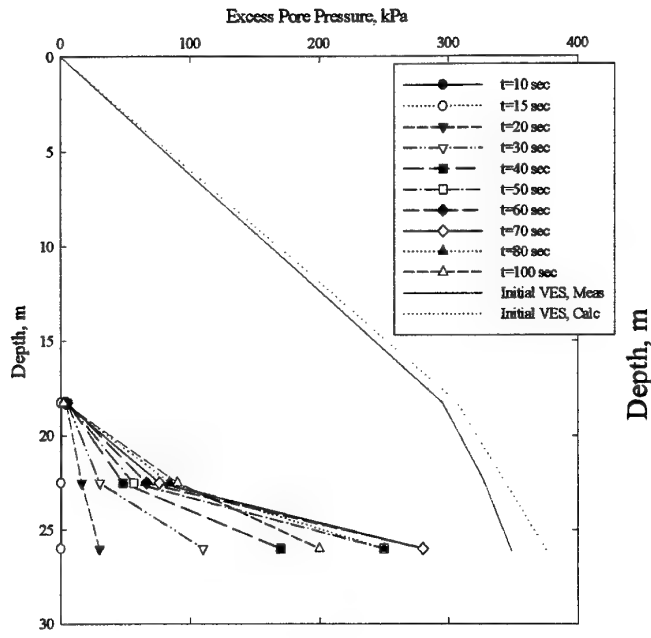
Model 4a-eq1

Cyclic Shear Strain, %
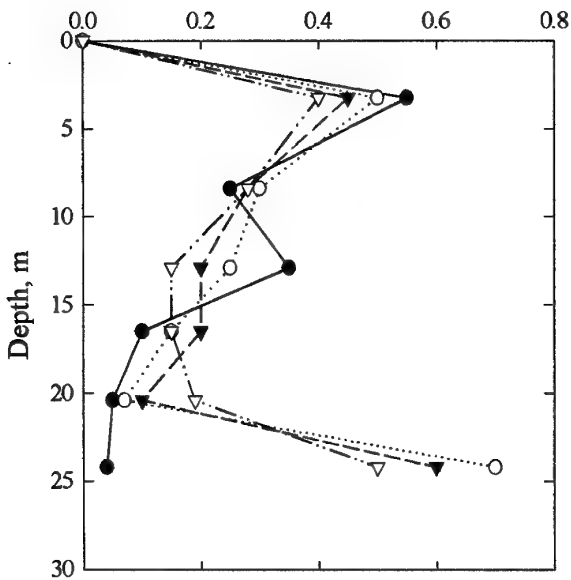
Model 4a-eq1

Cyclic Shear Stress, kPa
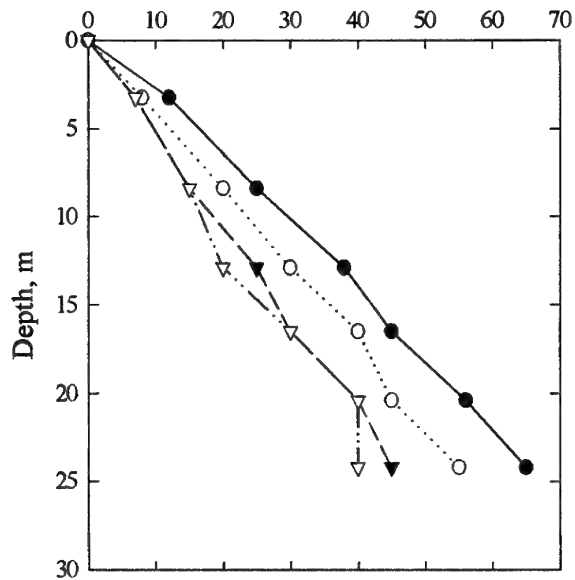
Model 4a Stress and strain isochrones

Model 4b

Model 4b-eq1

Excess Pore Pressure, kPa
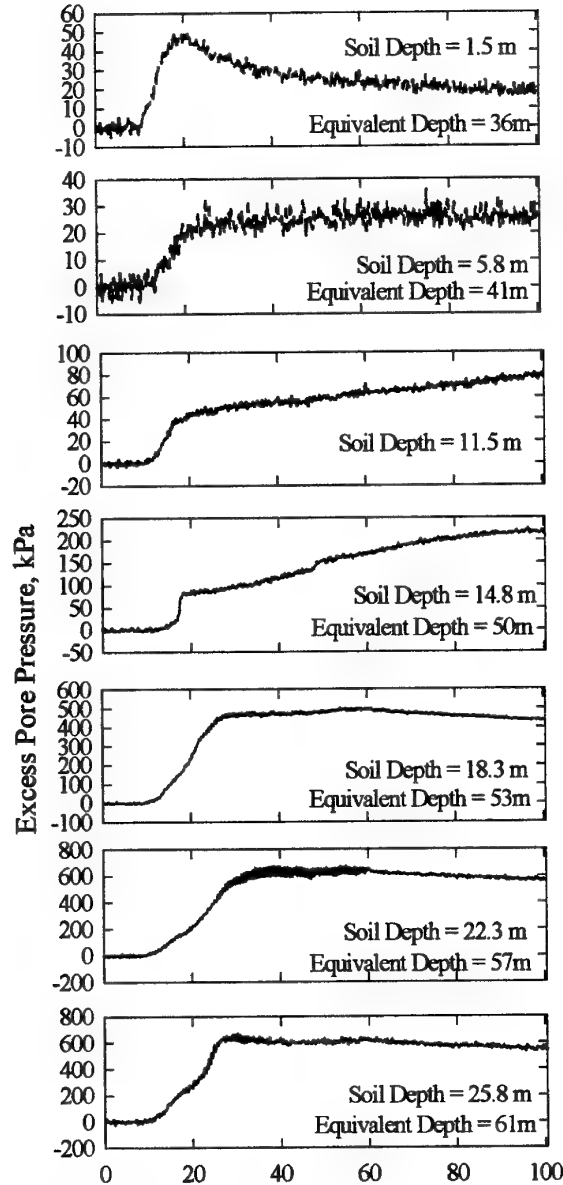
Cyclic Stress Ratio
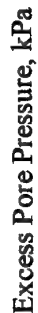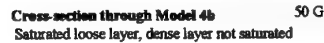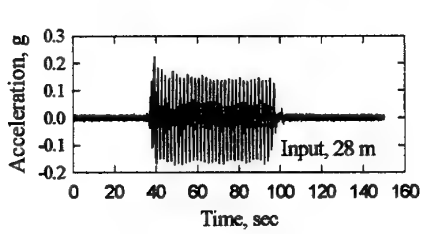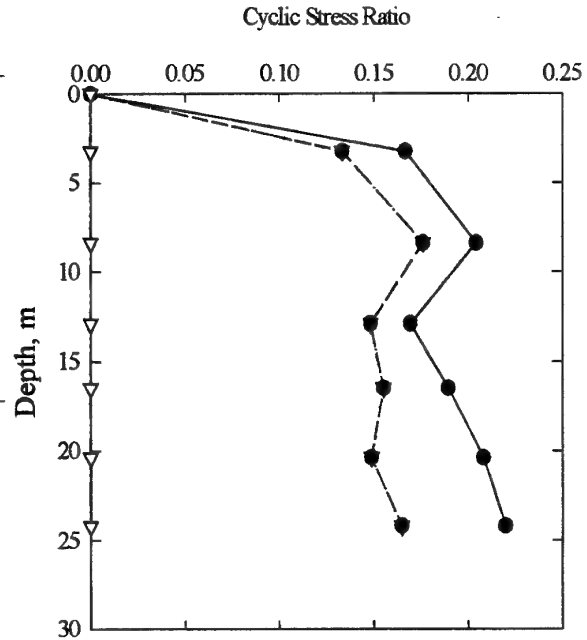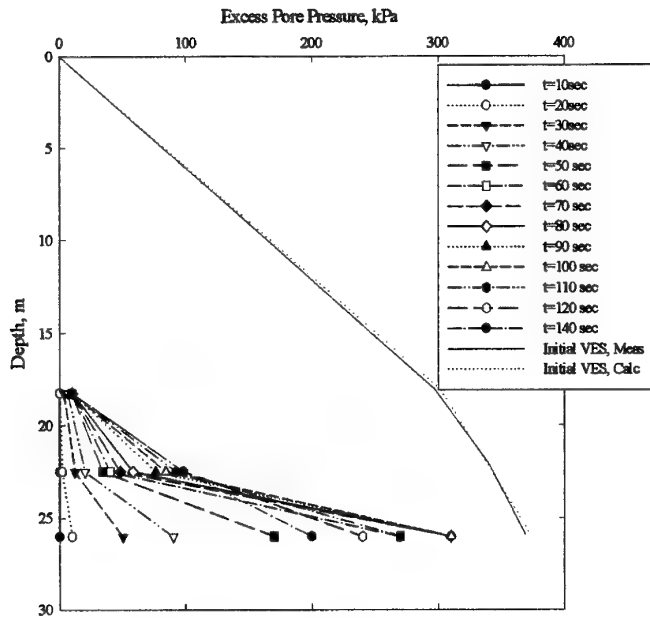
f = 0.6 Hz
a_{max} = 0.16 g

Model 4b-eq1

Cyclic Shear Strain, %
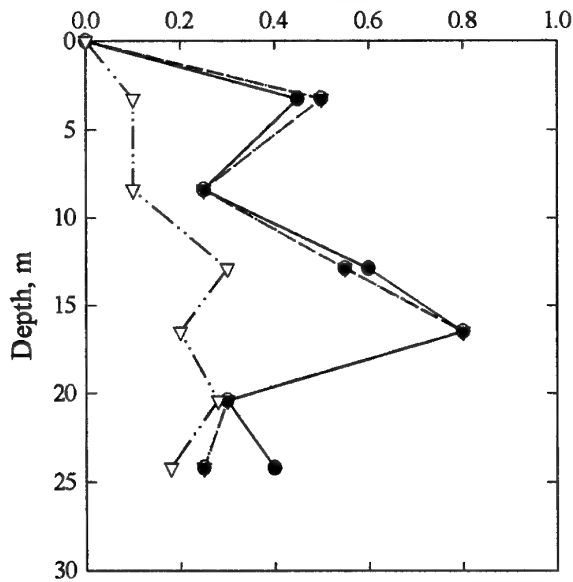
Model 4b-eq1

Cyclic Shear Stress, kPa
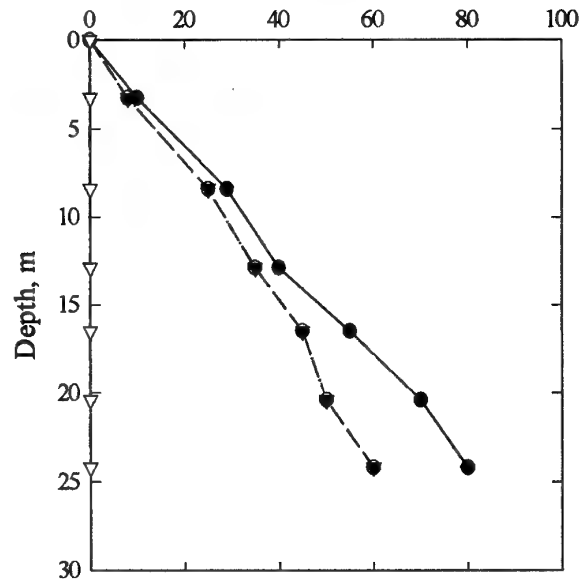
Model 4b Stress and strain isochrones

Model 4c

NOTE: Lead weight surcharge of 292 lbs over 347 in²
Surcharge at 50g 290 kPa, added 14.5 m of equivalent soil

f = 0.6 Hz
a_{max} = 0.08 g

Input, 28 m

Model 4c-eq1

Cyclic Shear Strain, %

Model 4c-eq1
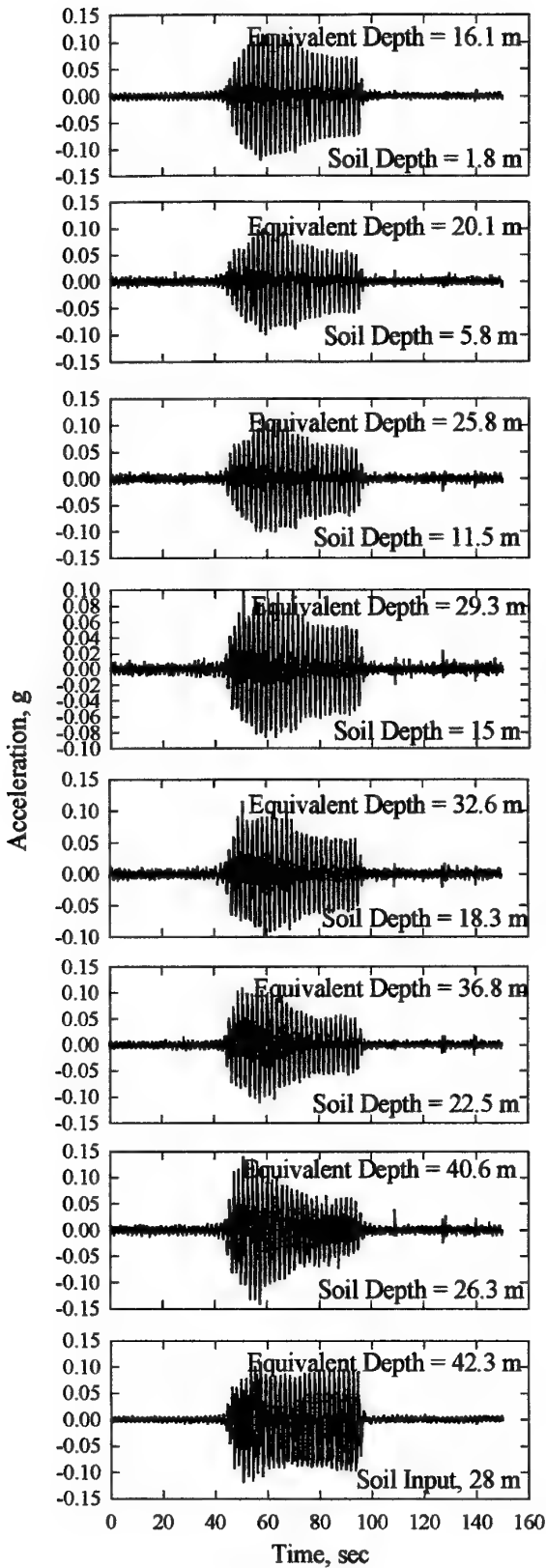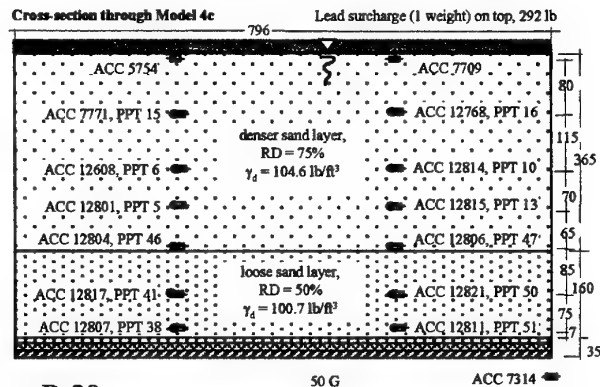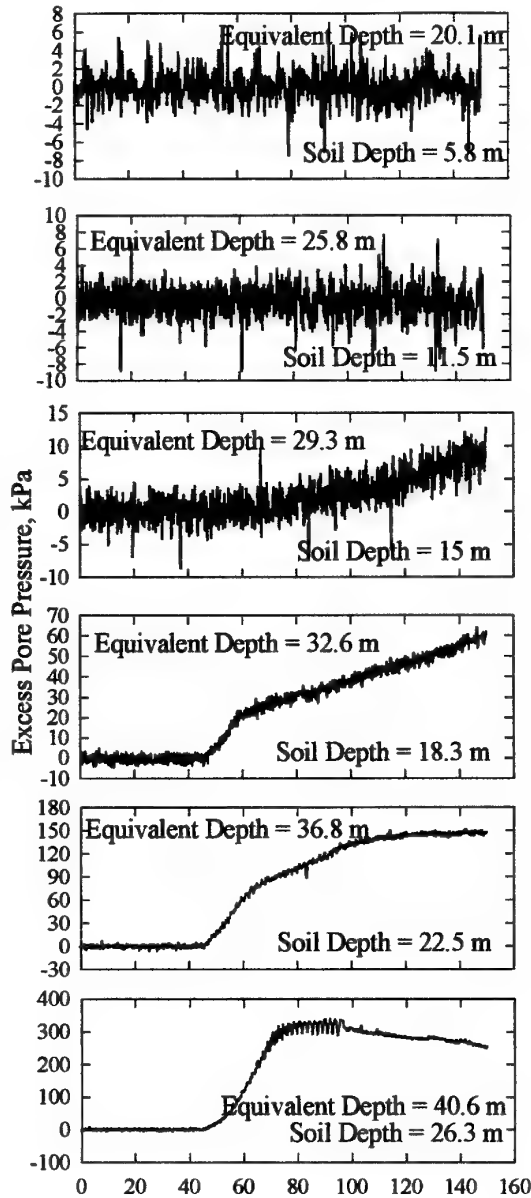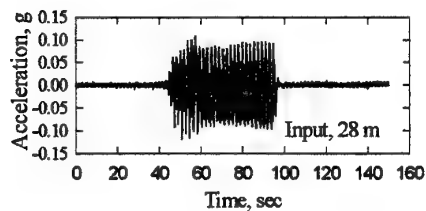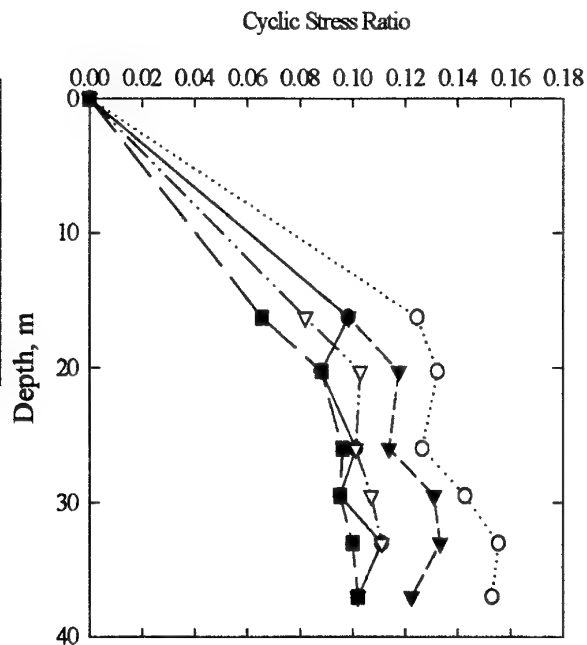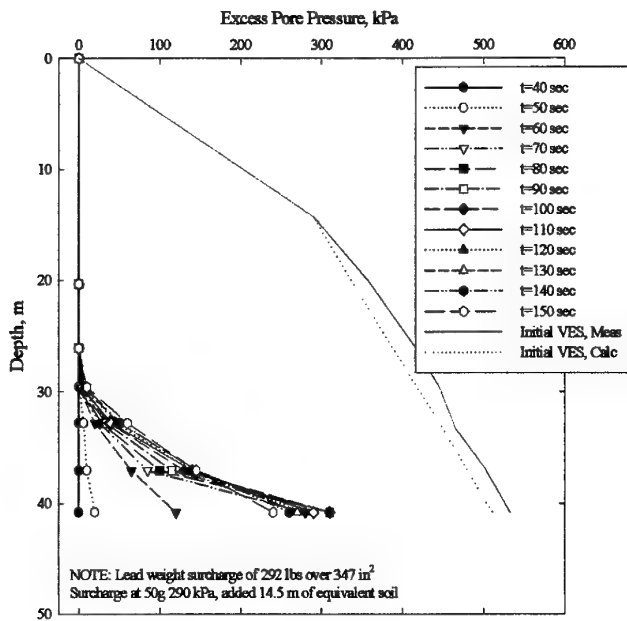
Cyclic Shear Stress, kPa
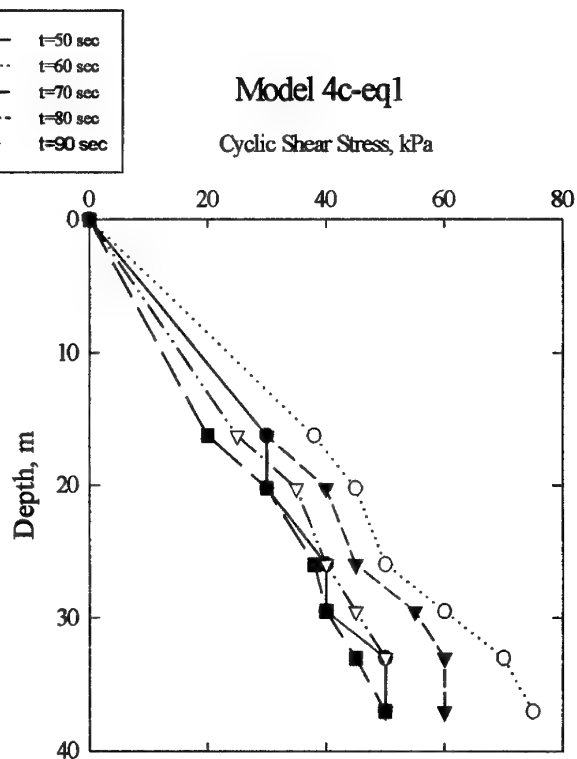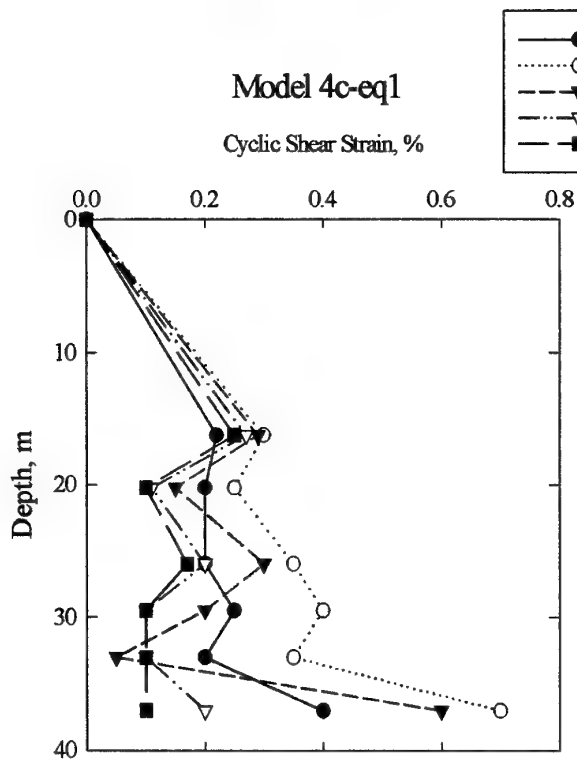
Model 4c Stress and strain isochrones

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Model 4d

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Model 4d-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

Legend:
- t=10 sec
- t=15 sec
- t=20 sec
- t=40 sec
- t=60 sec
- t=80 sec
- t=90 sec
- t=140 sec
- t=150 sec
- Initial VES, Meas
- Initial VES, Calc

NOTE: Lead weight surcharge of 294 lbs over 347 in^2
Surcharge at 50g 290 kPa, added 14.6 m equivalent soil

Soil Input, 28.2 m
Equivalent Input, 42 m

$f = 0.6$ Hz
$a_{max} = 0.1$ g

Legend:
- t=10 sec
- t=20 sec
- t=40 sec
- t=60 sec
- t=80 sec

Model 4d-eq1

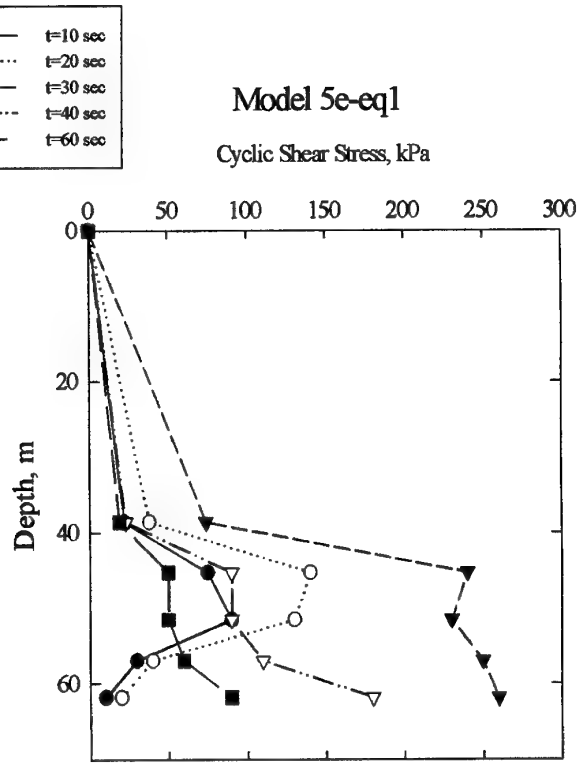Cyclic Shear Strain, %

Model 4d-eq1

Cyclic Shear Stress, kPa

Model 4d Stress and strain isochrones

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Model 4e

Model 4e-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

NOTE: Lead weight surcharge of 211 lbs over 347 in²
Surcharge at 50g, 209 kPa, added 10.3 m equivalent soil
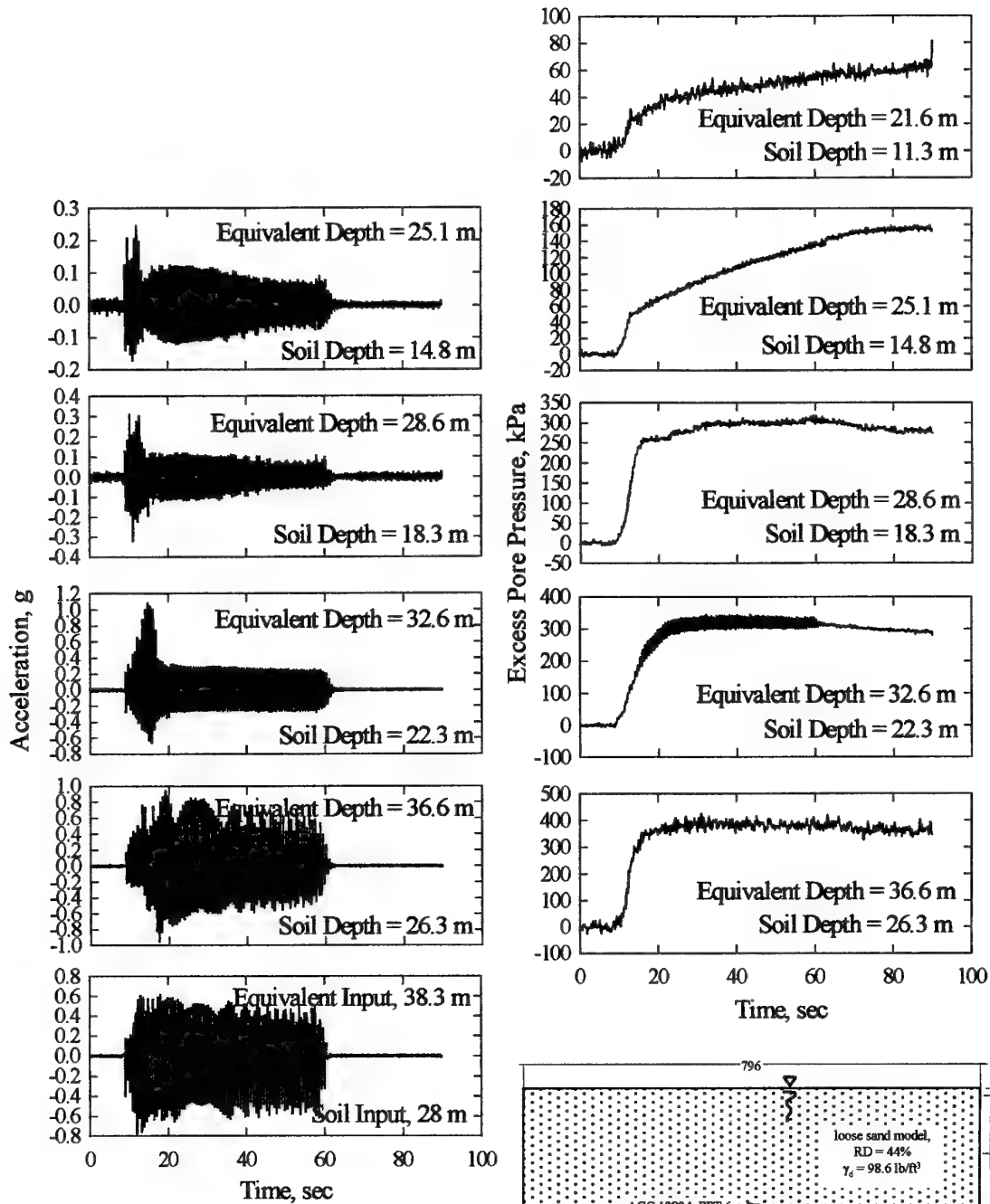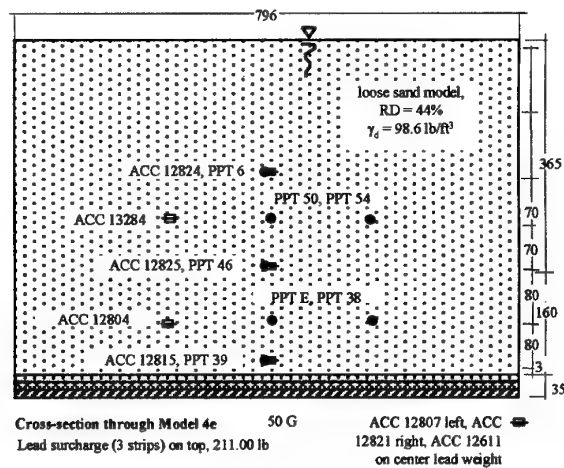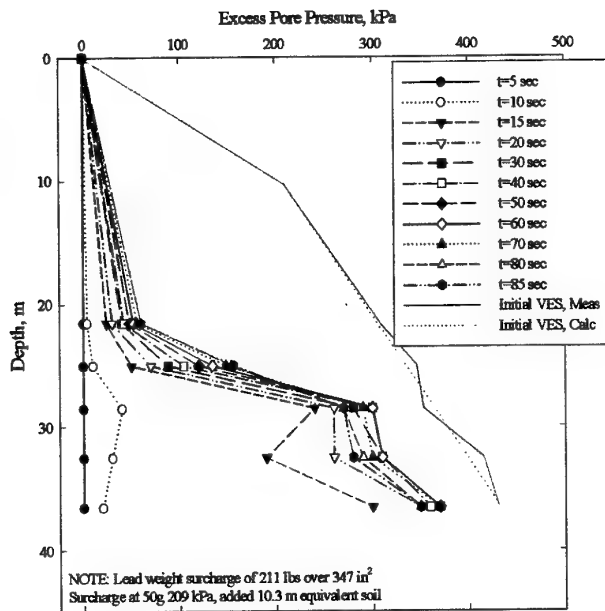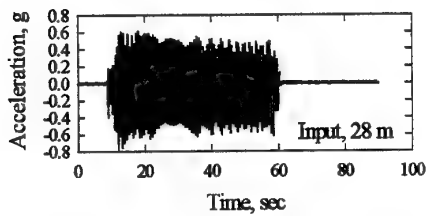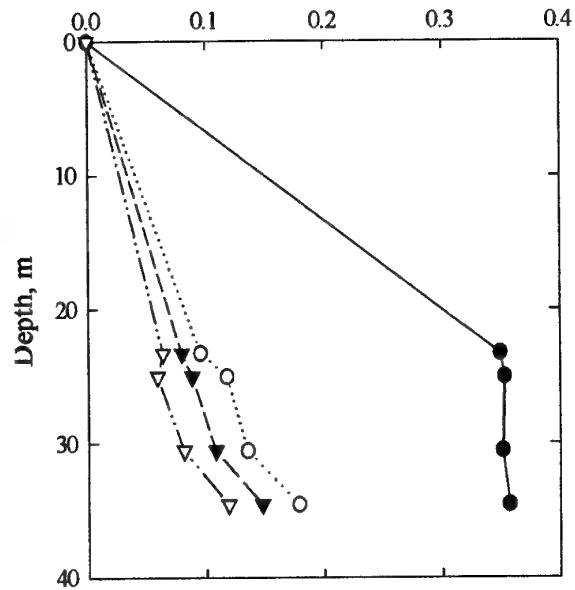
f = 1.5 Hz
a_{max} = 0.5 g
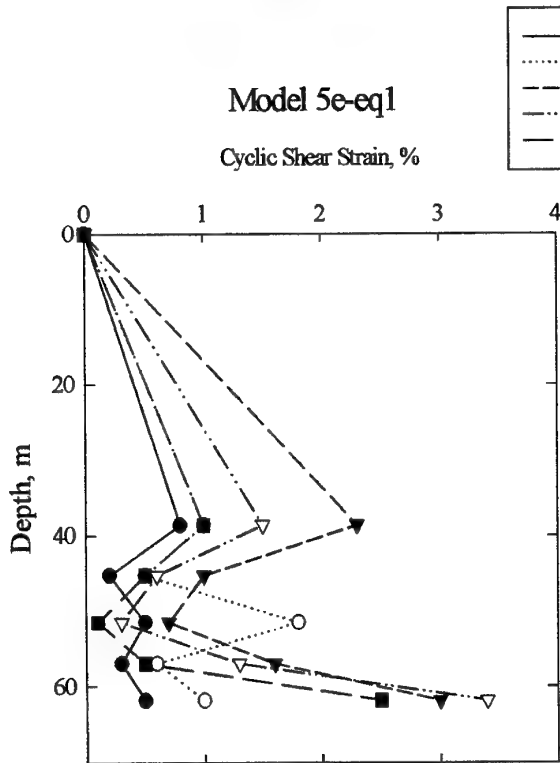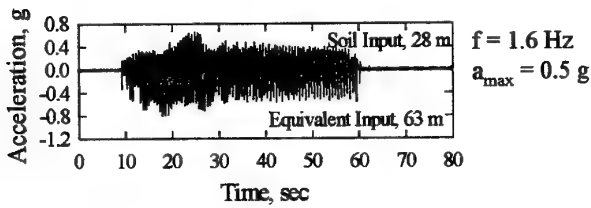
Model 4e-eq1

Cyclic Shear Strain, %
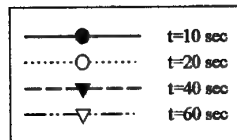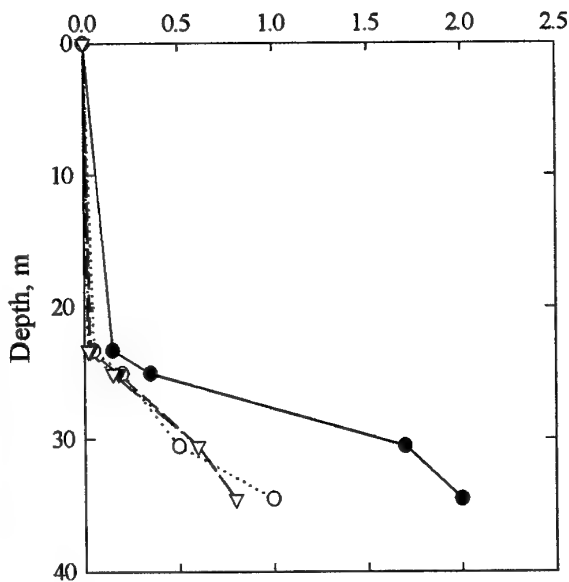
Model 4e-eq1

Cyclic Shear Stress, kPa
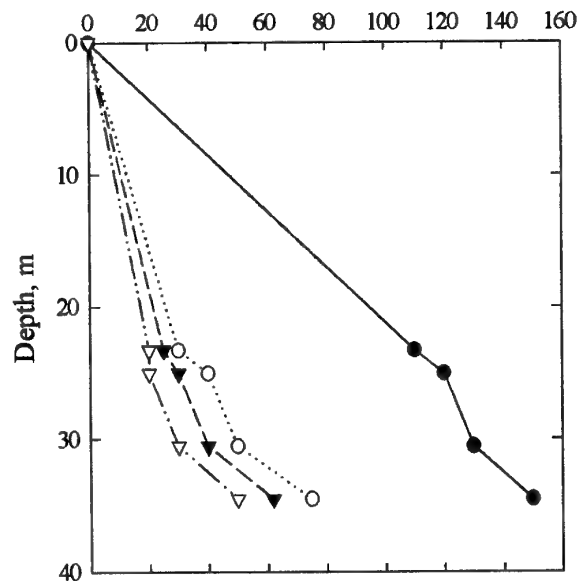
Model 4e Stress and strain isochrones
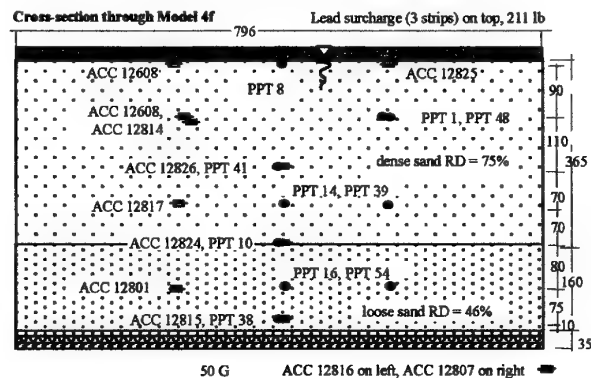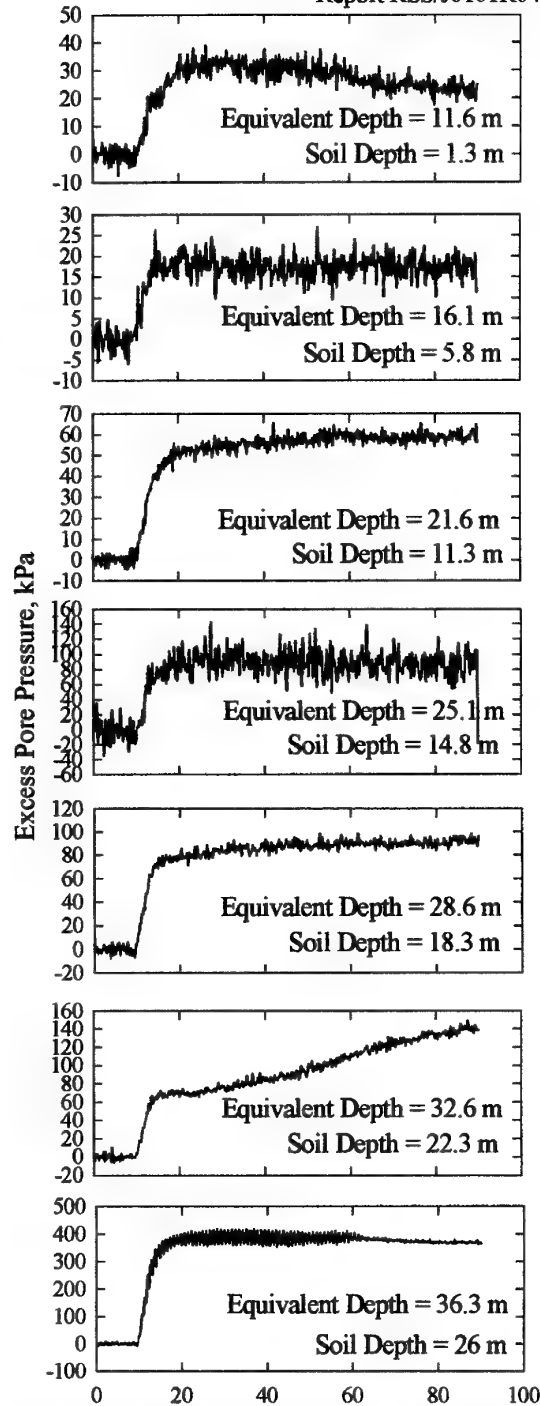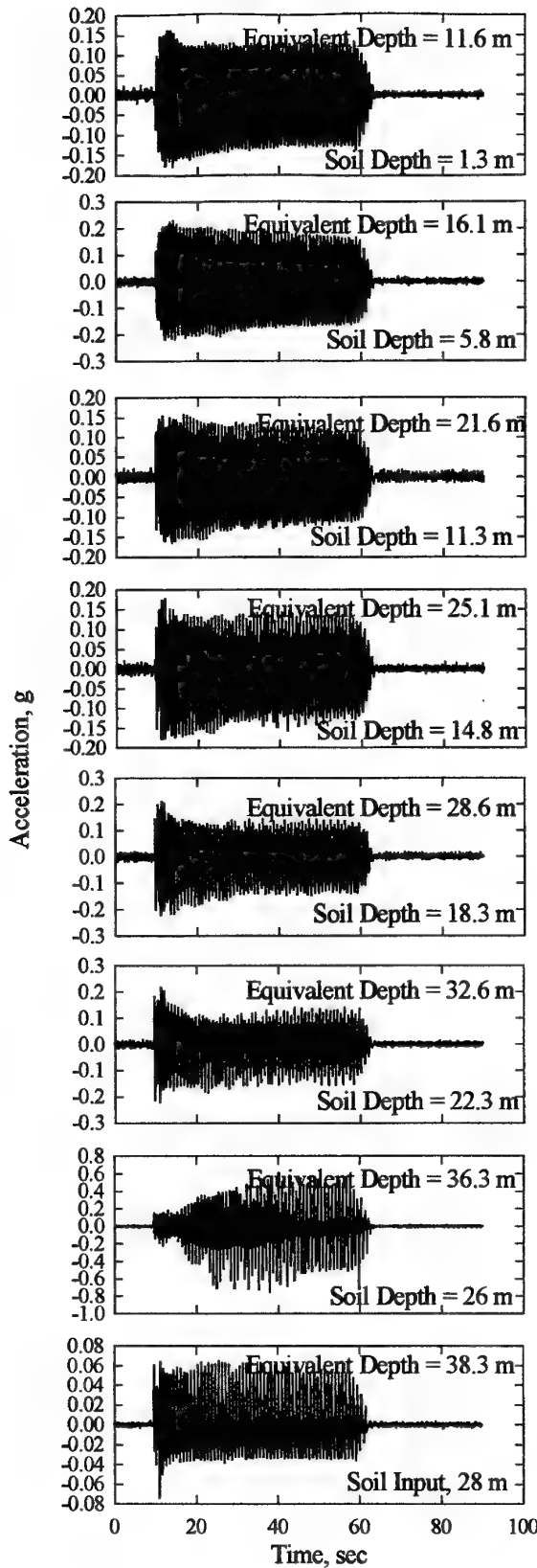
Model 4f

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Model 4f-eq1

Excess Pore Pressure, kPa
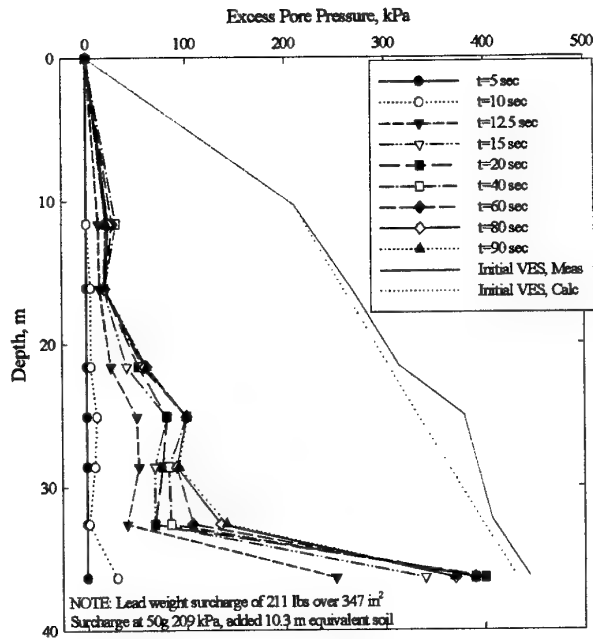
f = 1.2 Hz
a_{max} = 0.06 g

Cyclic Stress Ratio
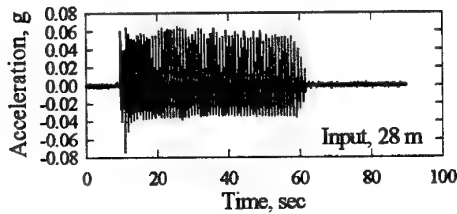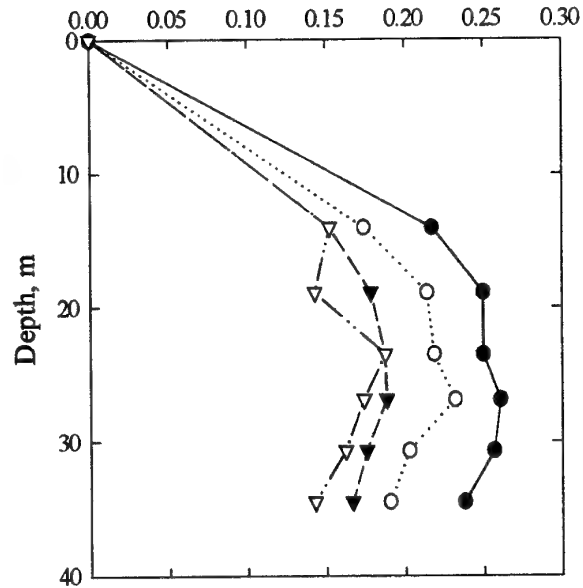
Model 4f-eq1

Cyclic Shear Strain, %

Model 4f-eq1

Cyclic Shear Stress, kPa

NOTE: Lead weight surcharge of 211 lbs over 347 in²
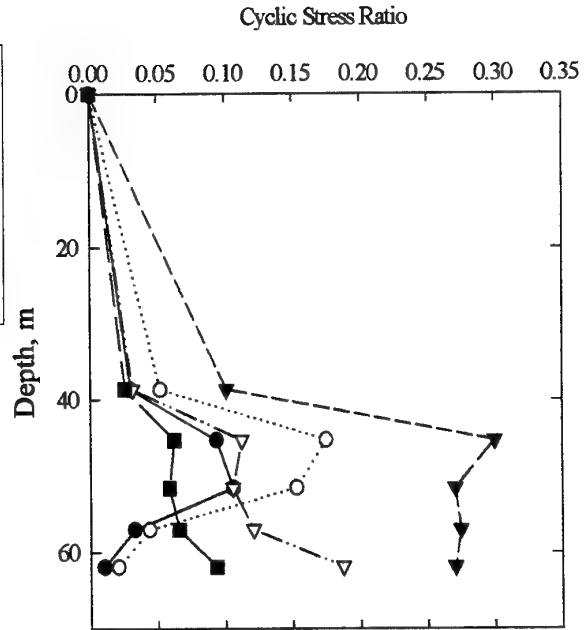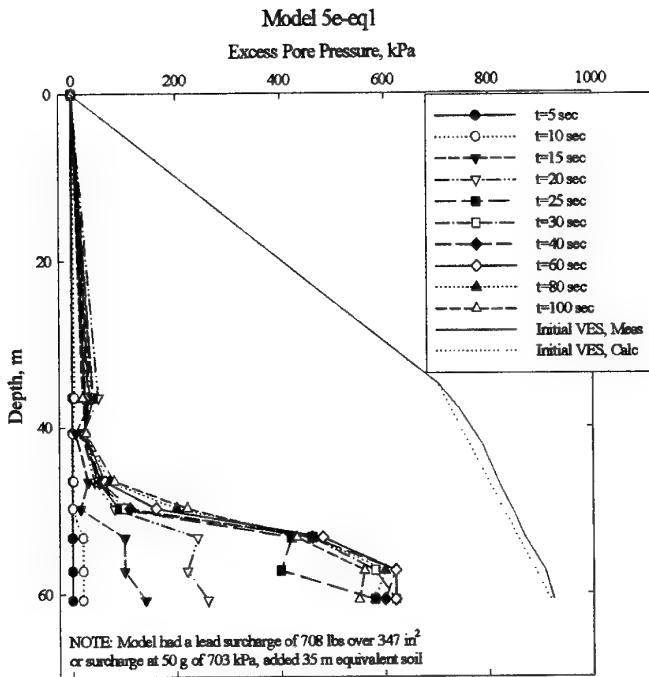Surcharge at 50g 209 kPa, added 10.3 m equivalent soil
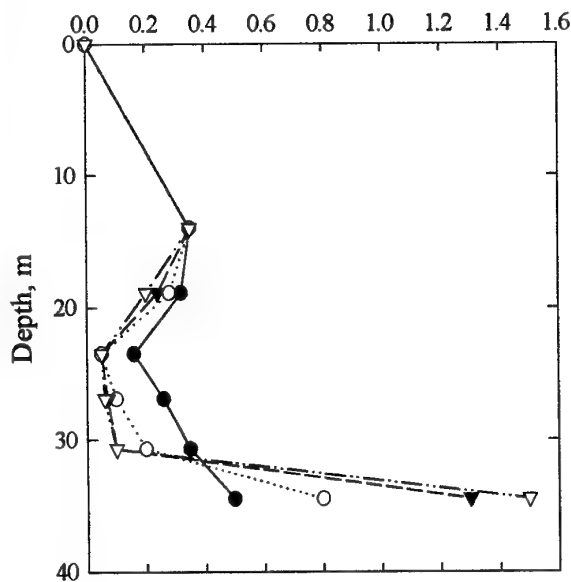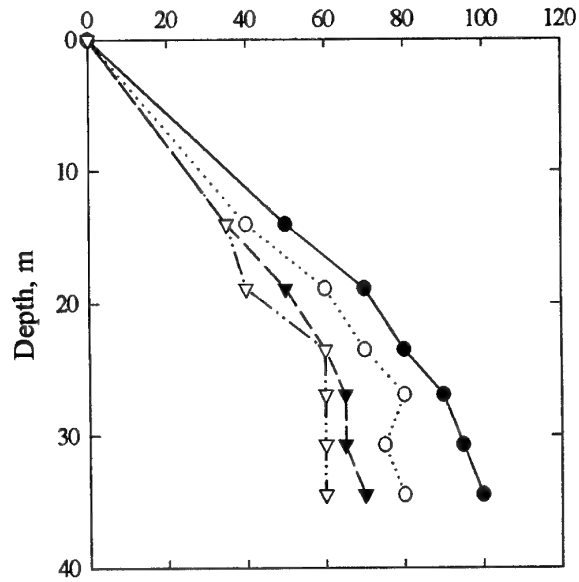
Model 4f Stress and strain isochrones

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Acceleration, g

Excess Pore Pressure, kPa

Time, sec

Model 4g

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Cross-section through Model 4g

Lead surcharge (3 strips) on top, 211 lb

loose sand model,
RD = 49%
γ_d = 99.4 lb/ft³

50G   ACC 12821 on left & ACC 12611 on right, ACC 12807 on center lead weight

Model 4g-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

Legend:
- t=5 sec
- t=10 sec
- t=12.5 sec
- t=15 sec
- t=20 sec
- t=30 sec
- t=40 sec
- t=50 sec
- t=60 sec
- t=70 sec
- t=80 sec
- t=90 sec
- Initial VES, Meas
- Initial VES, Calc

NOTE: Lead weight surcharge of 211 lbs over 347 in²
Surcharge at 50g 209 kPa, added 10.3 m equivalent soil

f = 1.15 Hz
a$_{max}$ = 0.3 g

Input, 28 m

Acceleration, g

Time, sec

Legend:
- t=10 sec
- t=20 sec
- t=30 sec
- t=40 sec
- t=60 sec

Model 4g-eq1

Cyclic Shear Strain, %

Model 4g-eq1

Cyclic Shear Stress, kPa

Model 4g Stress and strain isochrones

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Model 4h

Model 4h-eq1

Excess Pore Pressure, kPa

NOTE: Lead weight surcharge of 211 lbs over 347 in²
Surcharge at 50g 209 kPa, added 10.3 m equivalent soil

Cyclic Stress Ratio

f = 1.1 Hz
a_{max} = 0.25 g

Input, 28 m

Model 4h-eq1

Cyclic Shear Strain, %

Model 4h-eq1

Cyclic Shear Stress, kPa
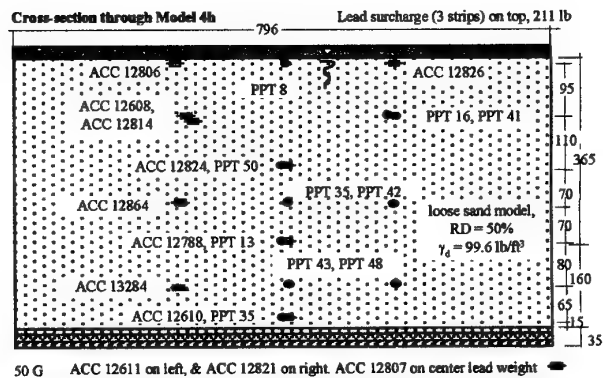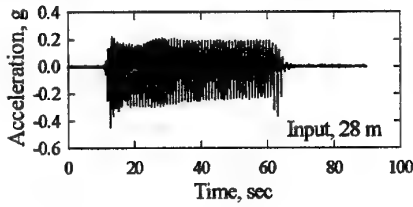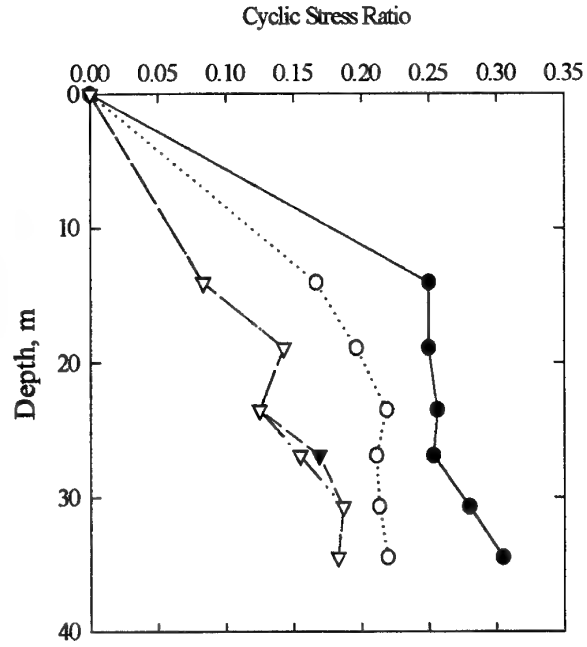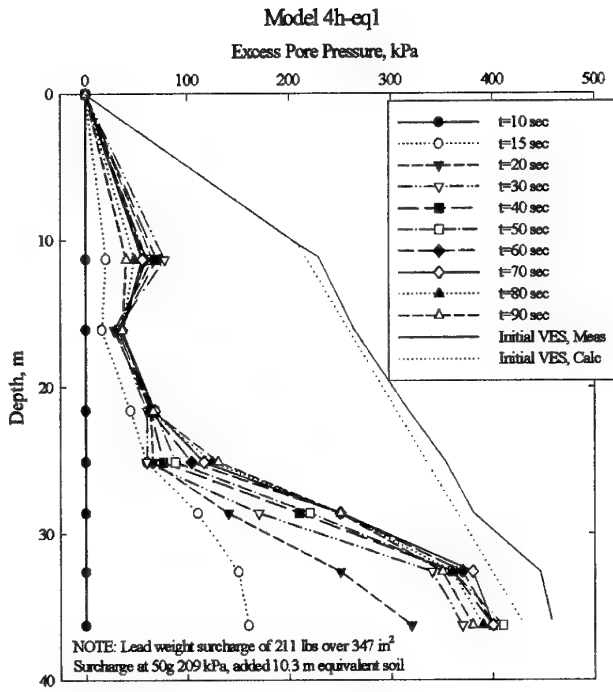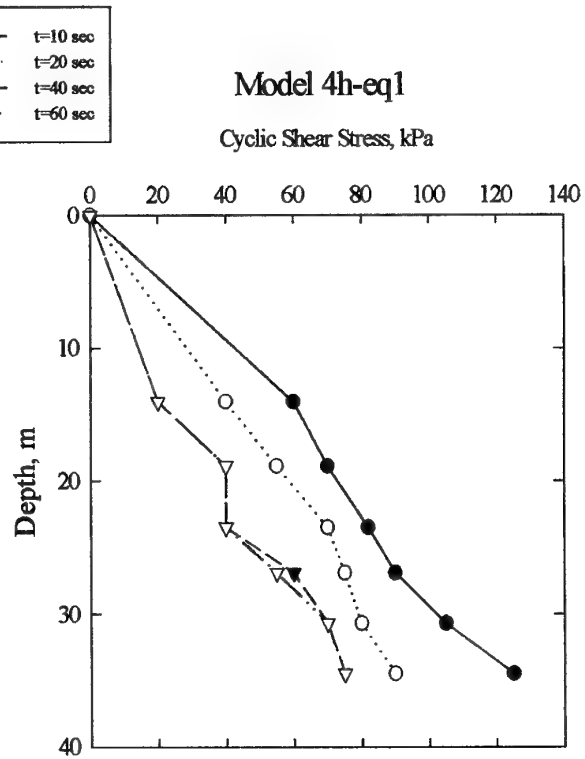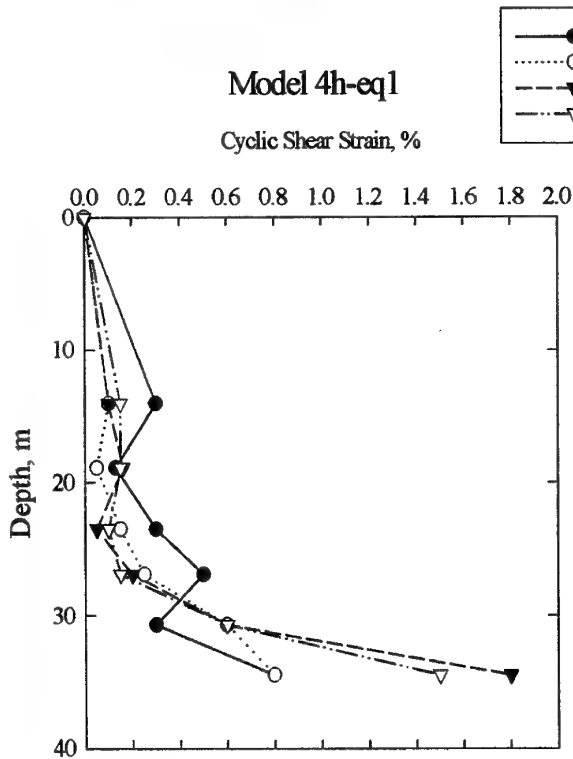
Model 4h Stress and strain isochrones

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Model 4i

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Model 4i-eq1

Excess Pore Pressure, kPa

Model 4i-eq1

Cyclic Stress Ratio

f = 1.1 Hz
a_{max} = 0.3 g

NOTE: Lead weight surcharge of 211 lbs over 347 in²
Surcharge at 50g 209 kPa, added 10.3 m equivalent soil

Model 4i-eq1

Cyclic Shear Strain, %

Model 4i-eq1

Cyclic Shear Stress, kPa
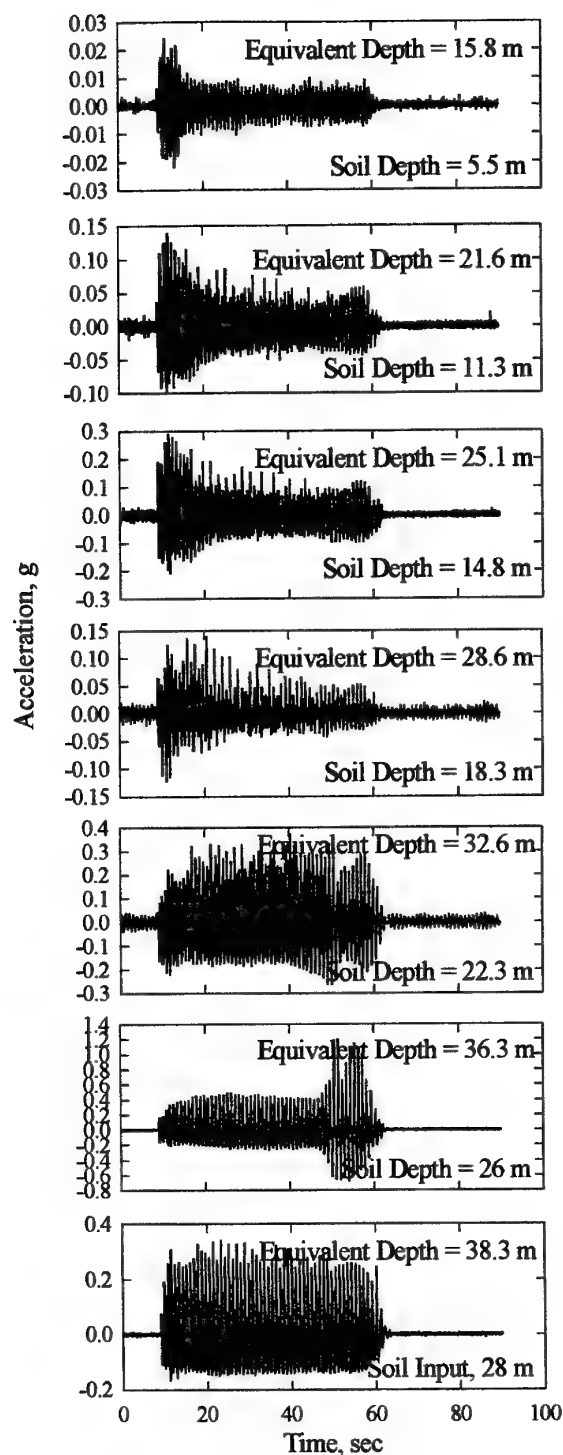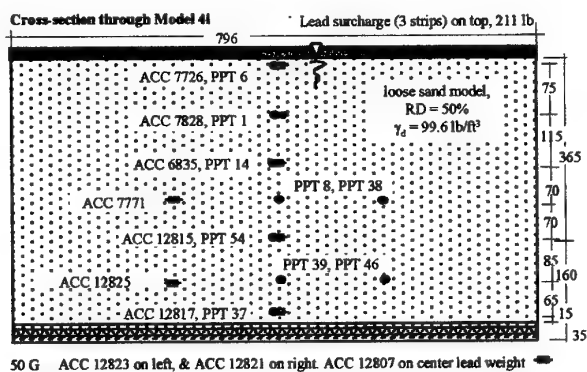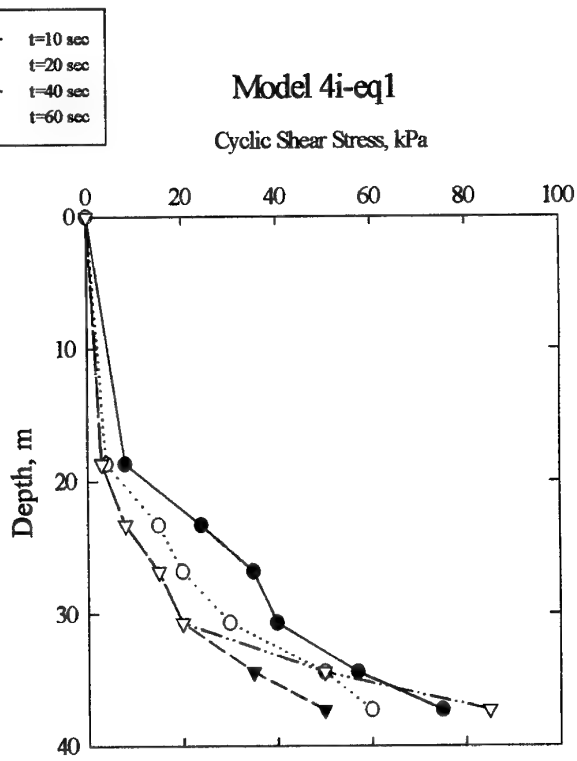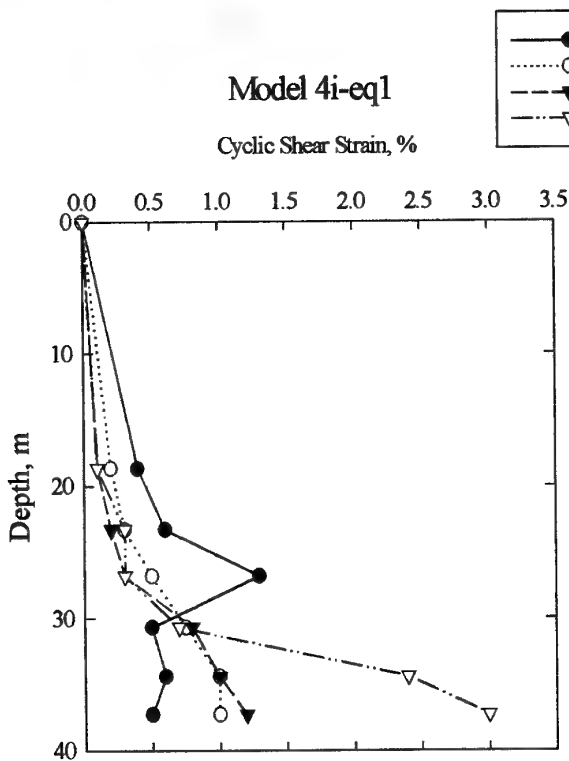
Model 4i Stress and strain isochrones

Model 4j

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Model 4j-eq1
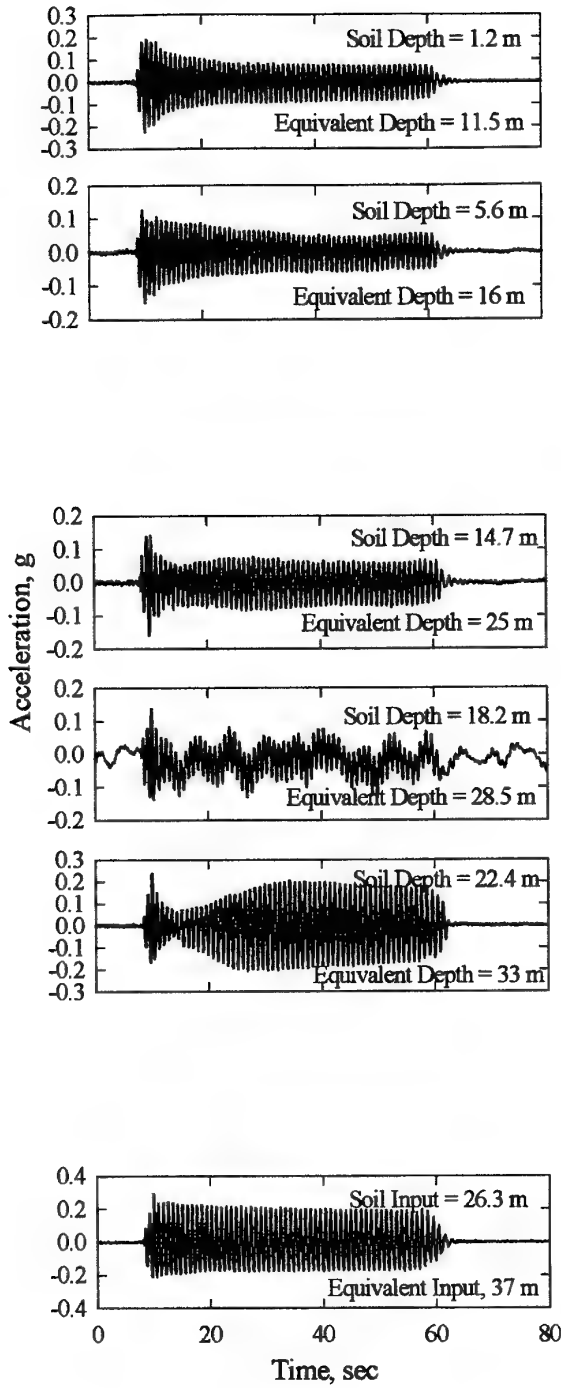
Model 4j Stress and strain isochrones

Model 4k

Cross-section through Model 4k   50 G   ACC 12823 on left, & ACC 12821 on right

Model 4k-eq1

Excess Pore Pressure, kPa

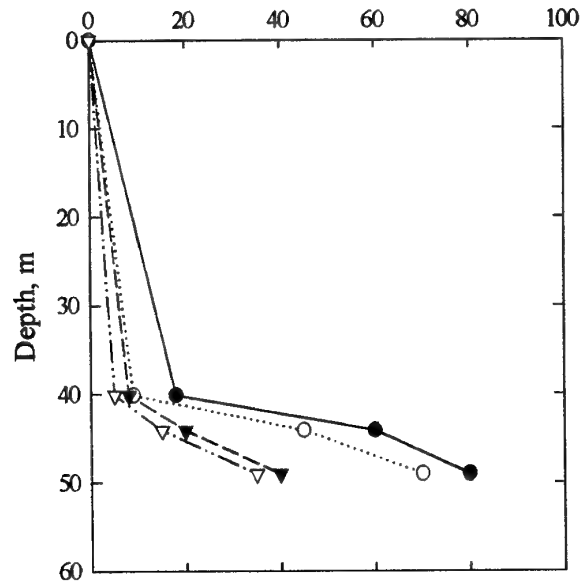Cyclic Stress Ratio

f = 1.1 Hz
a_{max} = 0.3 g

Input, 28 m

Model 4k-eq1

Cyclic Shear Strain, %

Model 4k-eq1

Cyclic Shear Stress, kPa

Model 4k Stress and strain isochrones

B-46

Equivalent Depth = 15.75 m
Soil Depth = 1.55 m

Equivalent Depth = 25.45 m
Soil Depth = 11.25 m

Equivalent Depth = 32.2 m
Soil Depth = 18 m

Equivalent Depth = 36.4 m
Soil Depth = 22.2 m

Equivalent Depth = 40.4 m
Soil Depth = 26.2 m

Equivalent Input, 42.2 m
Soil Input, 28 m

Acceleration, g

Time, secs

Equivalent Depth = 25.2 m
Soil Depth = 11m

Equivalent Depth = 28.95 m
Soil Depth = 14.75m

Equivalent Depth = 32.2 m
Soil Depth = 18m

Equivalent Depth = 36.4 m
Soil Depth = 22.2m

Equivalent Depth = 40.4 m
Soil Depth = 26.2m

Excess Pore Pressure, kPa

Lead surcharge on top, 295 lb

796

phreatic surface
above soil surface

Hacc 6835

PPT 46

A12611

A12823

denser sand layer,
RD = 75%

Hacc 7828

RPT 53

A12804

PPT 41

A12821

PPT 43

Hacc 12608

A12817

loose sand layer, RD = 50%

A12801

PPT 39

Hacc 12806

PPT 48

A12814

PPT 35

Hacc 12610

PPT 37

A13284

79

115

70

365

65

83

160

80

2

35

Cross-section through Model 4l

Laser LVDT in center of box to
measure expansion

50G

ACC12826
on table

Model 4l

B-47

Model 4l (Box Sticking)

Excess Pore Pressure, kPa

Cyclic Stress Ratio

Legend:
- t=12.5sec
- t=25 sec
- t=37.5sec
- t=50sec
- t=75sec
- t=100 sec
- t=150 sec
- t=200 sec
- Initial VES, Meas
- Initial VES, Calc

Note: model had 295.3 lb surcharge
293.1 kPa at 50 g, added 14.5 m equivalent soil

Soil Input, 28 m

Equivalent Input, 42.5 m

f = 1.5 Hz
a_{max} = 0.6 g

Acceleration, g

Time, secs

Legend:
- t=20 sec
- t=40 sec
- t=60 sec

Model 4l-eq1

Cyclic Shear Strain, %

Model 4l-eq1

Cyclic Shear Stress, kPa

Depth, m

Model 4l Stress and strain isochrones

B-48

Model 5a

Model 5a-eq1

Excess Pore Pressure, kPa

f = 0.6 Hz
a_max = 0.09 g

Cyclic Stress Ratio

NOTE: Model had a lead surcharge of 586 lbs over 347 in²
or surcharge at 50 g of 581 kPa, added 27.8 m equivalent soil
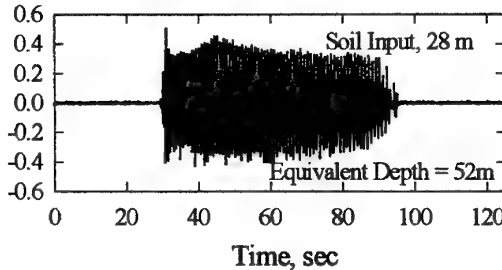
Model 5a-eq1

Cyclic Shear Strain, %

Model 5a-eq1

Cyclic Shear Stress, kPa
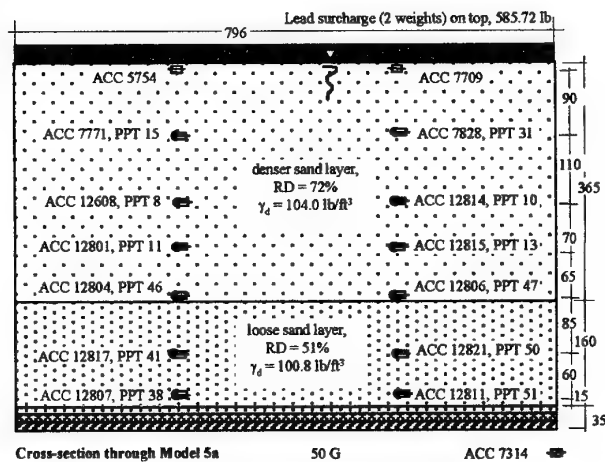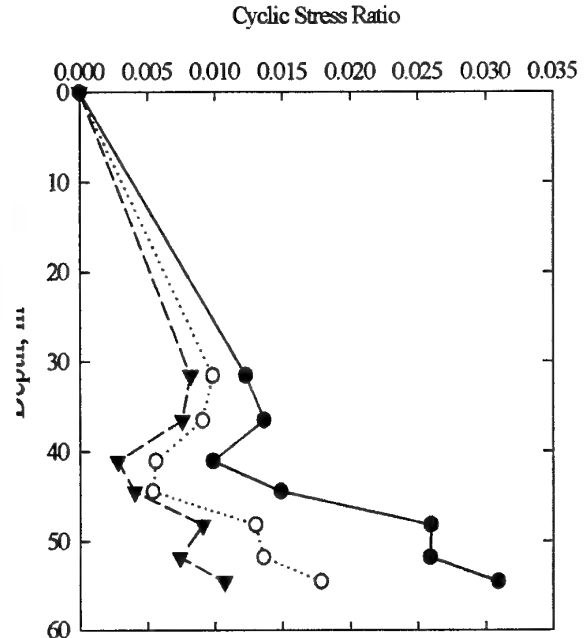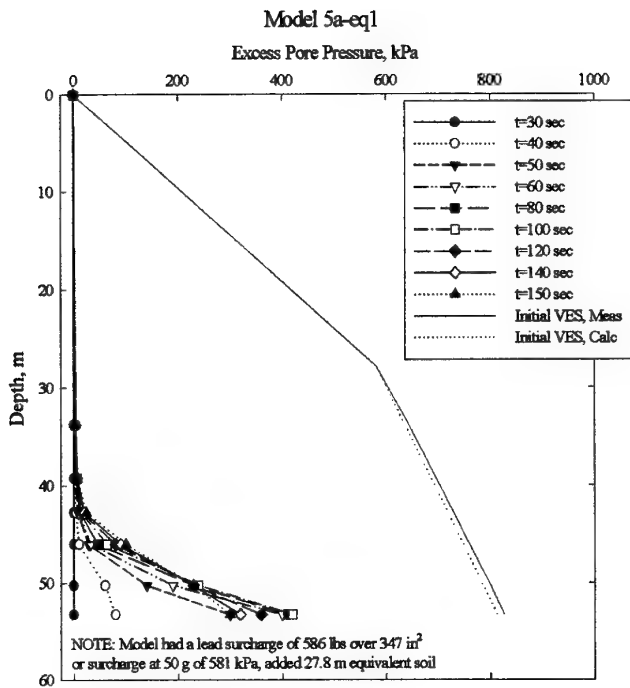
Model 5a Stress and strain isochrones

Model 5b

Cross-section through Model 5b   50 G   ACC 7314

Model 5b-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

	t=35 sec
	t=40 sec
	t=50 sec
	t=60 sec
	t=80 sec
	t=100 sec
	t=120 sec
	t=140 sec
	t=150 sec
	Initial VES, Meas
	Initial VES, Calc

NOTE: Model had a lead surcharge of 586 lbs over 347 in²
or surcharge at 50 g of 581 kPa, added 27.7 m equivalent soil

f = 0.6 Hz
a_{max} = 0.12 g

Soil Input, 28 m

Equivalent Input, 56 m

	t=10 sec
	t=20 sec
	t=30 sec
	t=40 sec
	t=50 sec

Model 5b-eq1

Model 5b-eq1

Cyclic Shear Strain, %

Cyclic Shear Stress, kPa

Model 5b Stress and strain isochrones

B-52

WES ref. # 19
Nevada Sand # 1   Lead surcharge (2 weights & 4 strips) on top, 585.72 lb

This test generated no useable data,
Eq1 and 2 were particularly poor, Eq3 may
have produced some information.

Model 5c

Cross-section through Model 5c

Model 5d

Cross-section through Model 5d   50 G   ACC 7828

Model 5d-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

NOTE: Model had a lead surcharge of 775 lbs over 347 in²
or surcharge at 50 g of 769 kPa, added 37 m equivalent soil
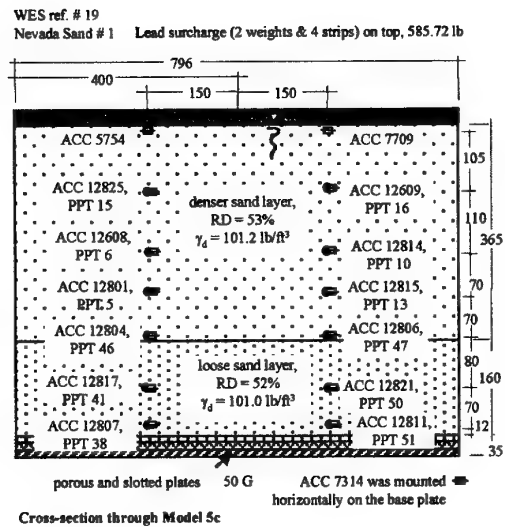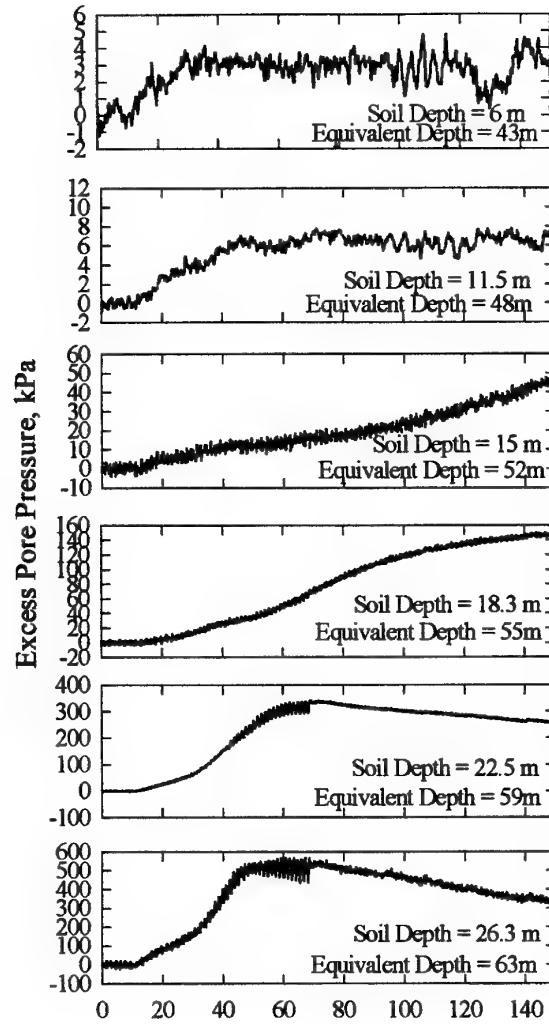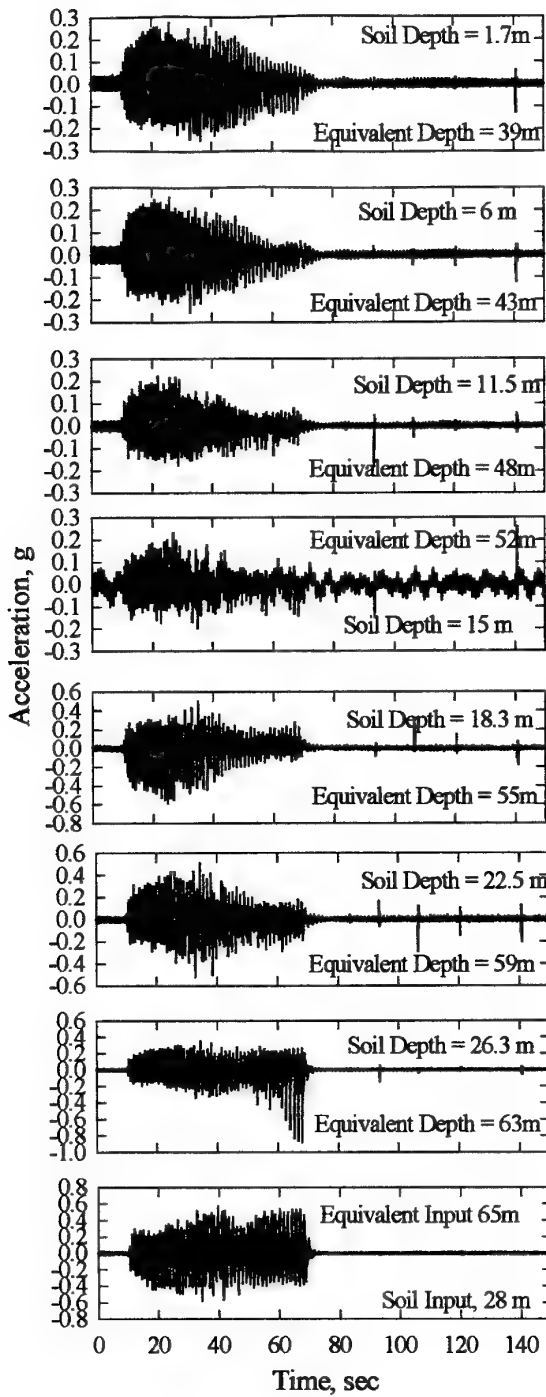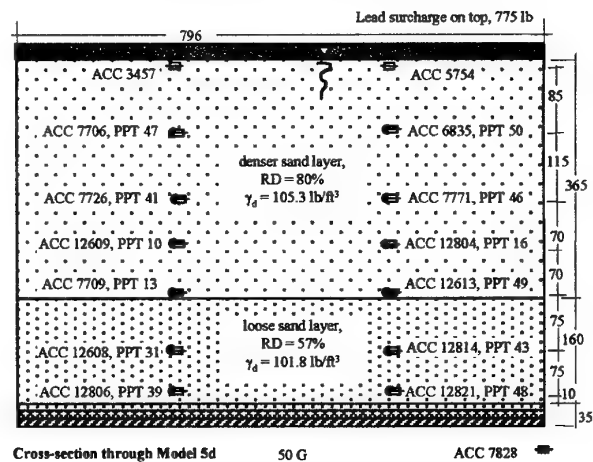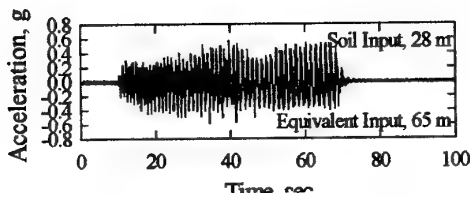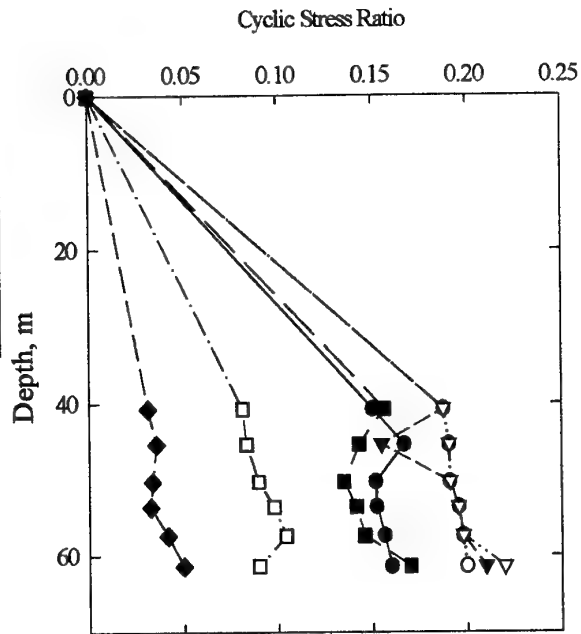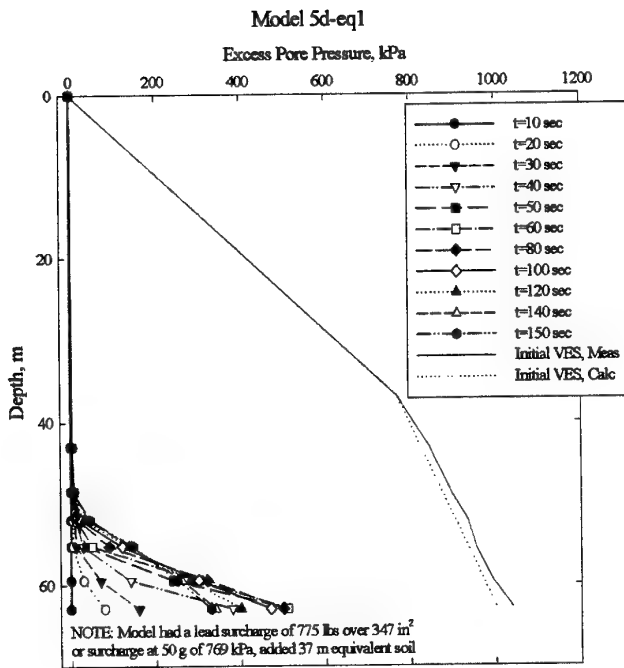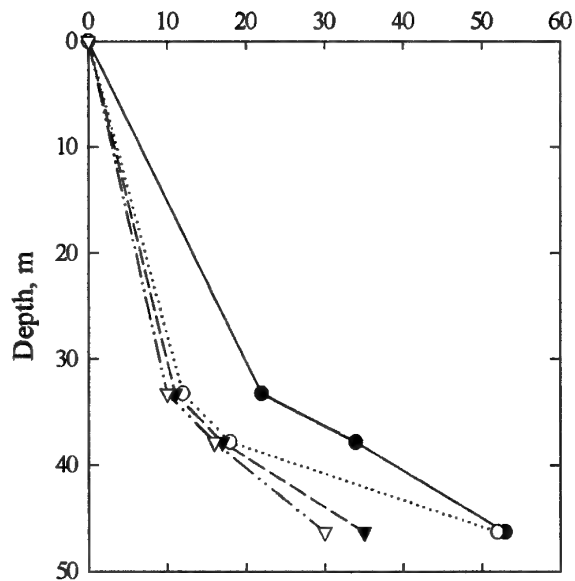
f = 1.6 Hz
a_{max} = 0.5 g

Model 5d-eq1

Cyclic Shear Strain, %
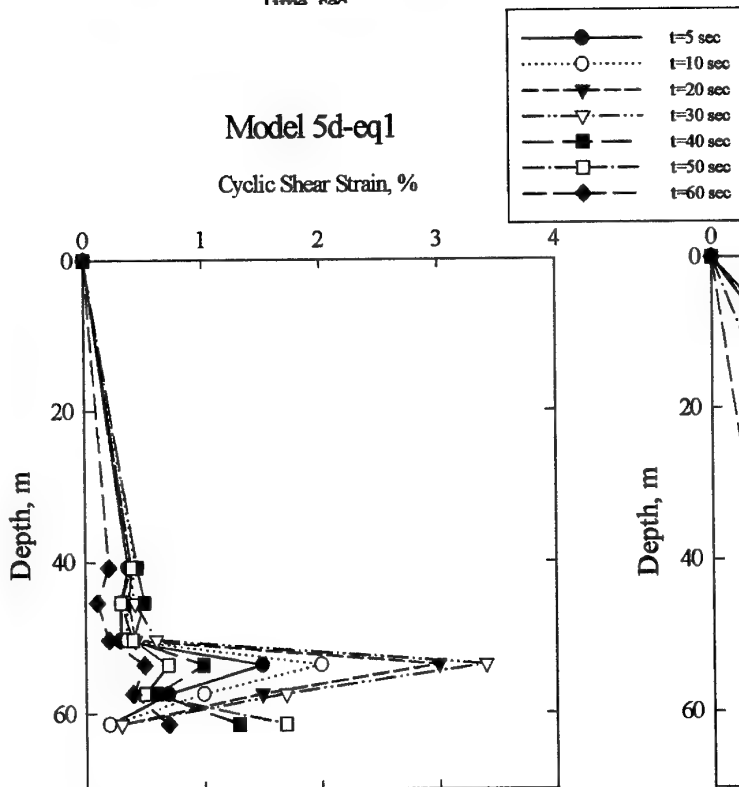
Model 5d-eq1

Cyclic Shear Stress, kPa
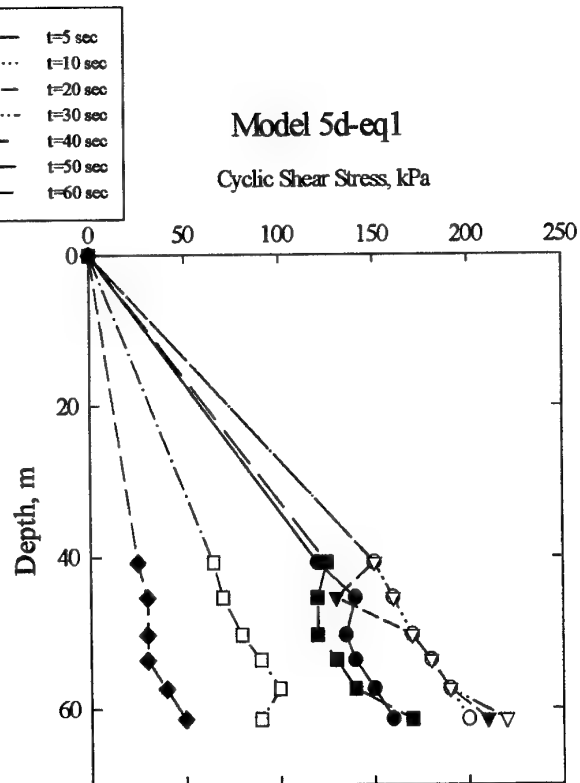
Model 5d Stress and strain isochrones
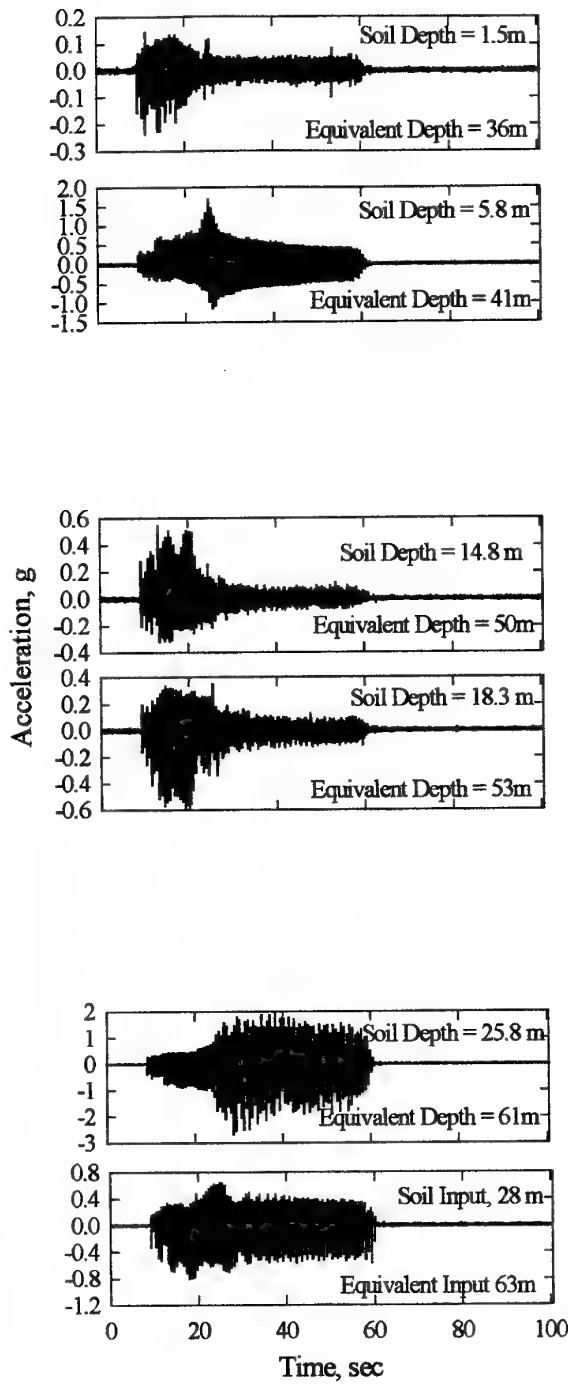
Model 5e
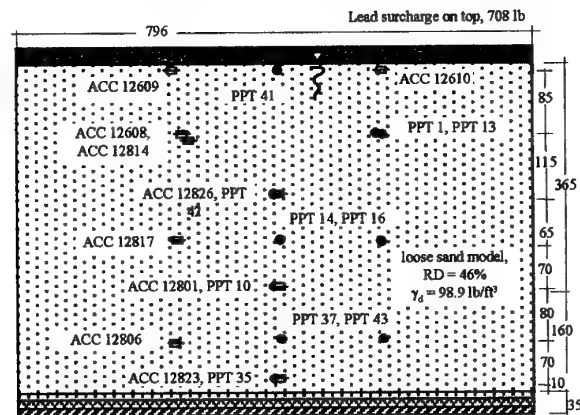
Cross-section through Model 5e   50 G   ACC 12821 left, ACC 12807 right

Model 5e-eq1

Excess Pore Pressure, kPa

Cyclic Stress Ratio

NOTE: Model had a lead surcharge of 708 lbs over 347 in² or surcharge at 50 g of 703 kPa, added 35 m equivalent soil

Soil Input, 28 m $f = 1.6$ Hz

$a_{max} = 0.5$ g

Equivalent Input, 63 m

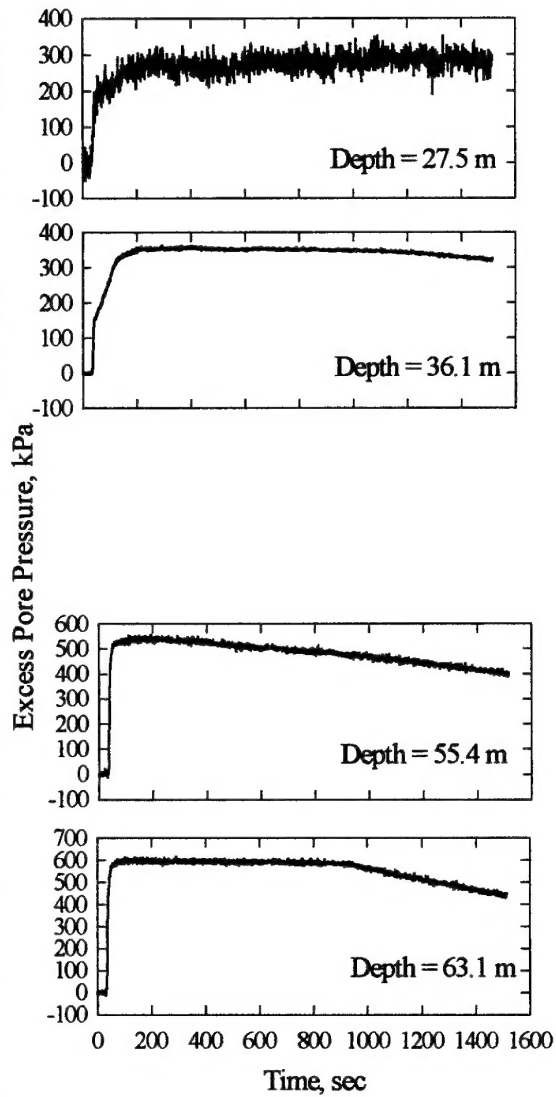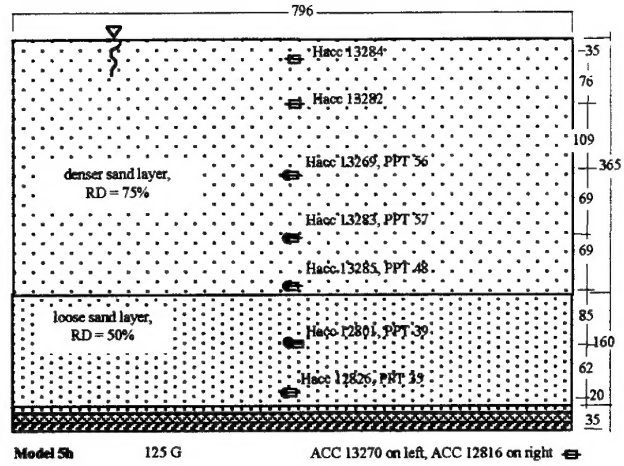Time, sec

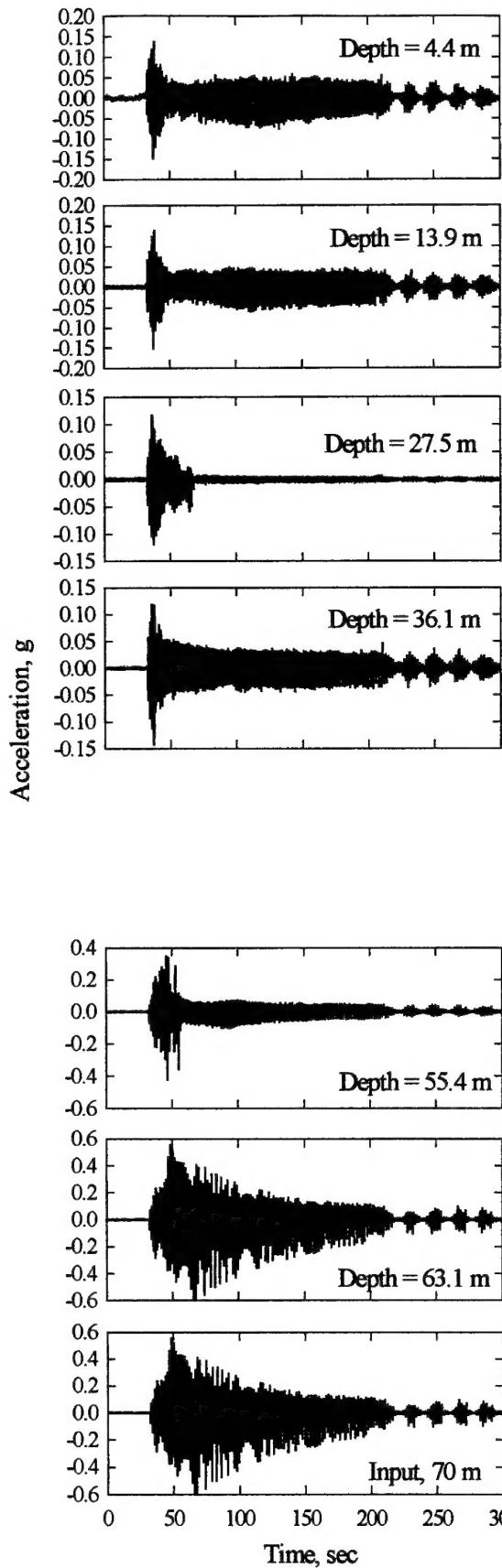Model 5e-eq1

Cyclic Shear Strain, %

Model 5e-eq1

Cyclic Shear Stress, kPa

Model 5e Stress and strain isochrones

Model 5f

Model 5f (Arch 1)

Excess Pore Pressure, kPa

Cyclic Stress Ratio

f = 1.6 Hz
a_{max} = 0.8 g

Note: model had 495 lb surcharge
491.5 kPa at 50 g, added 23.9 m equivalent soil

Soil Input, 28 m
Equivalent Input, 52 m
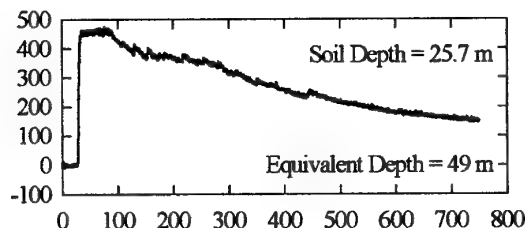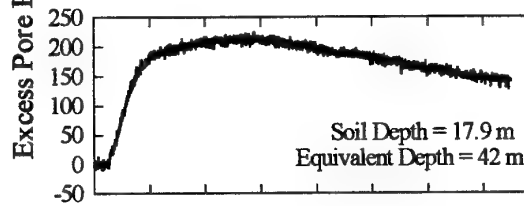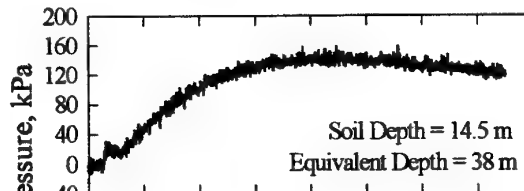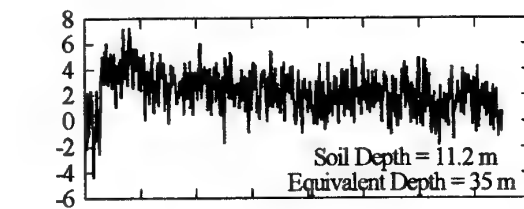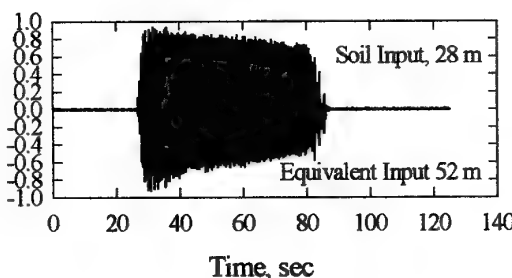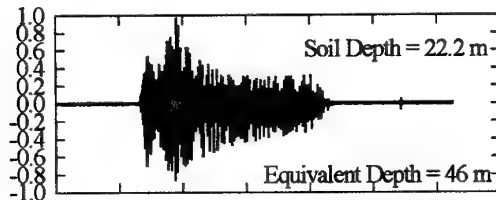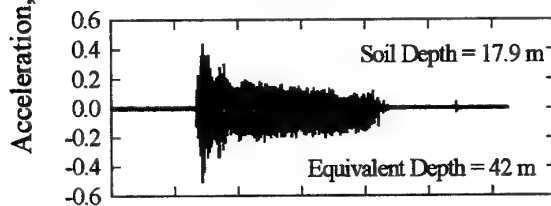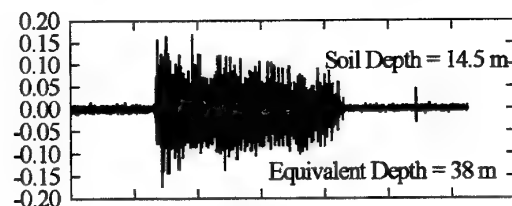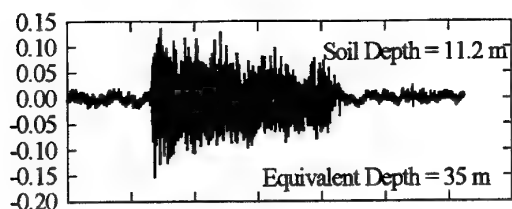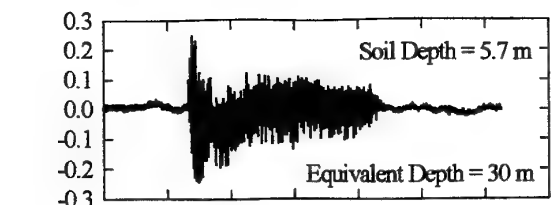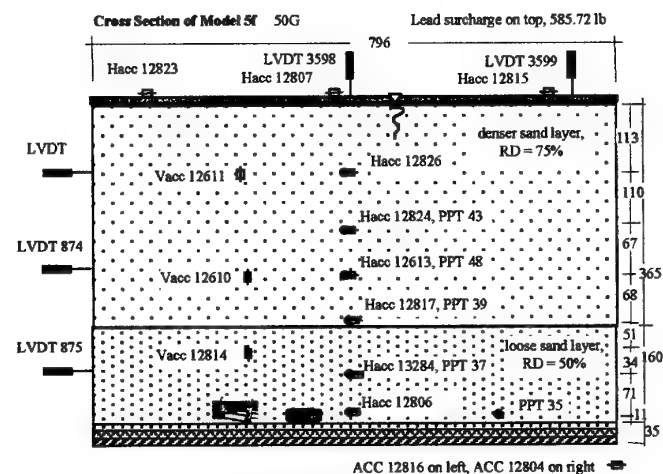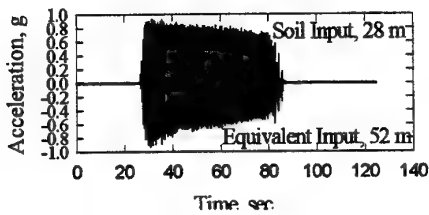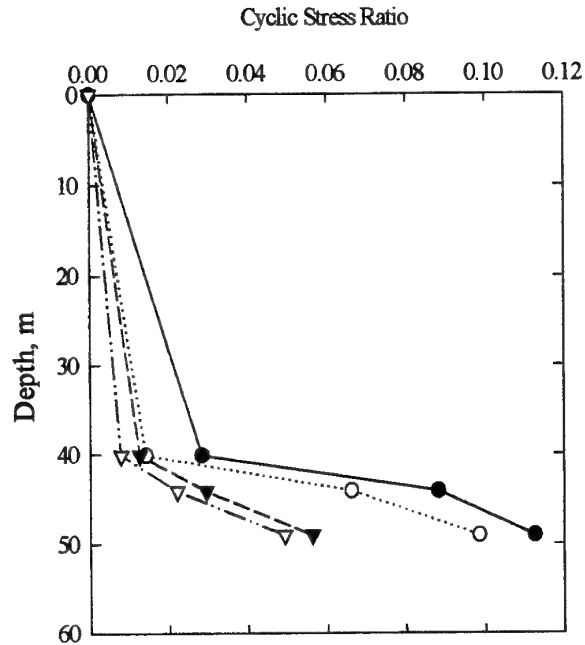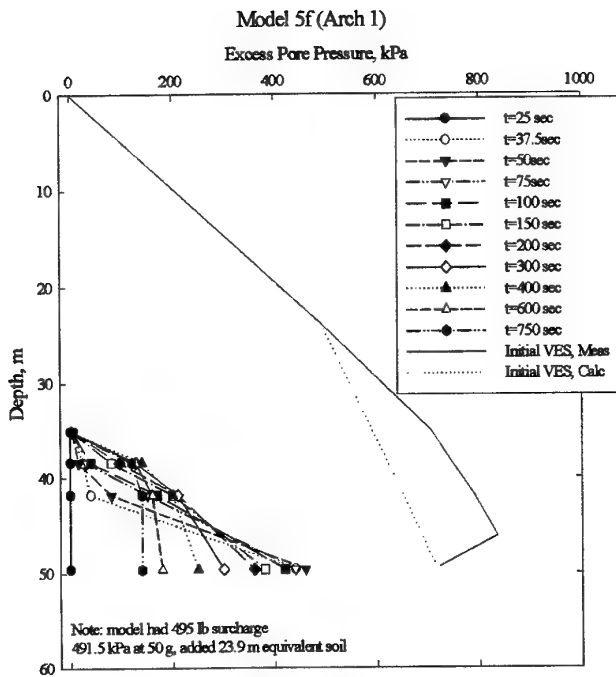
Model 5f-eq1

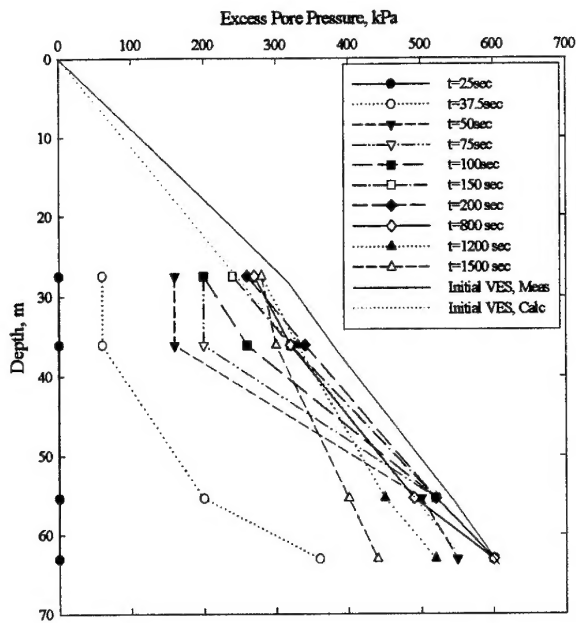Cyclic Shear Strain, %
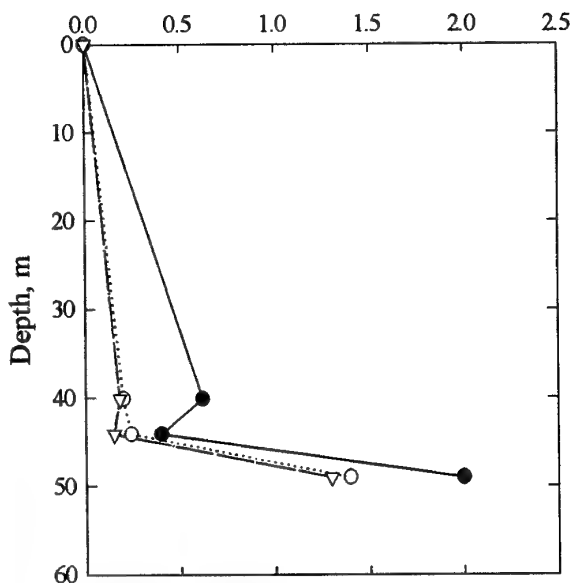
Model 5f-eq1

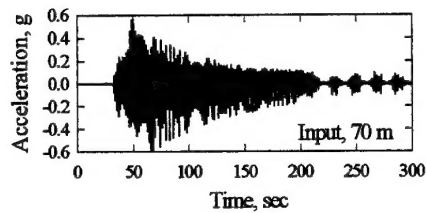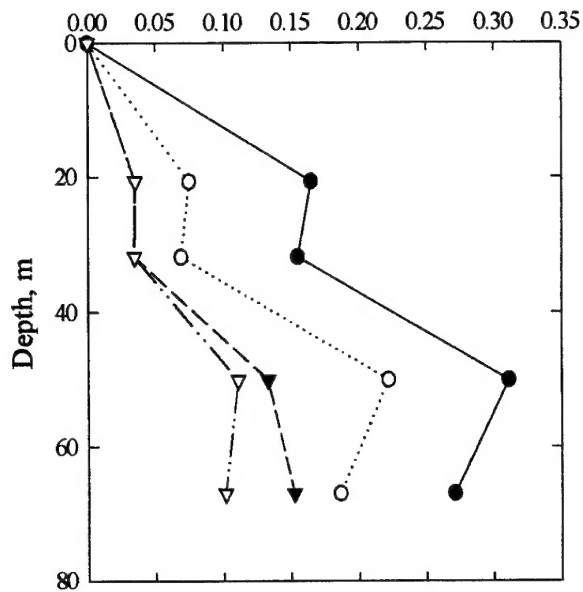Cyclic Shear Stress, kPa
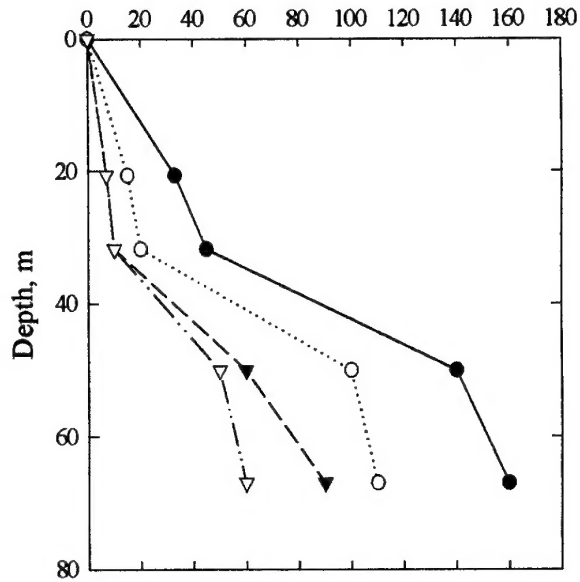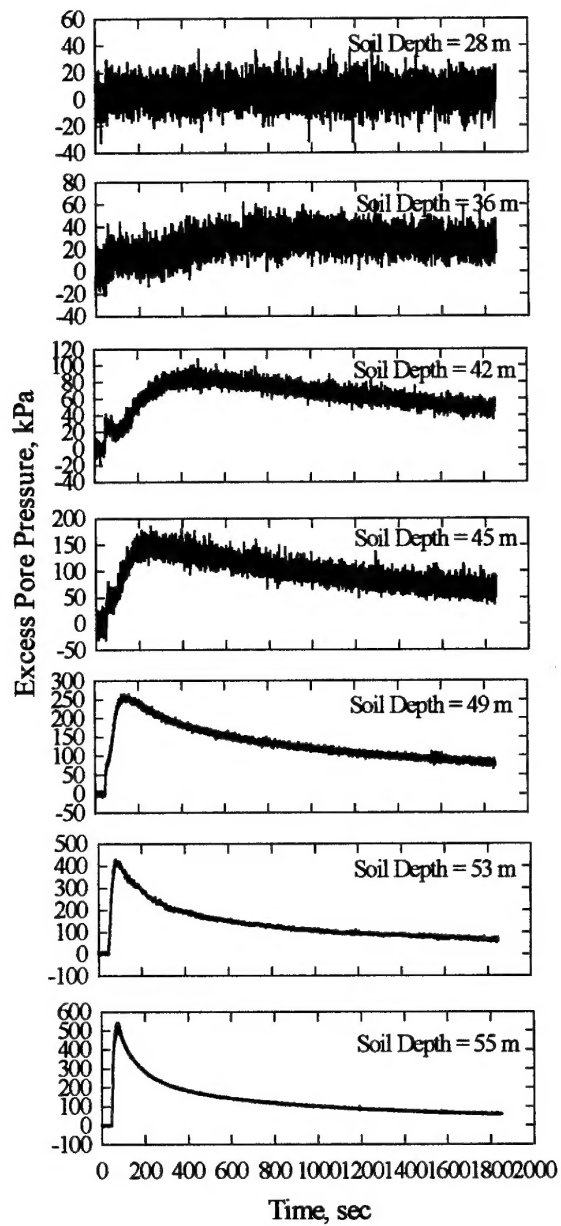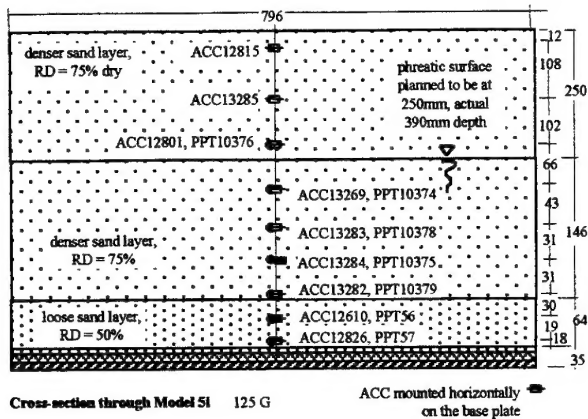
Model 5f Stress and strain isochrones

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Legend (upper):
t=25 sec
t=37.5sec
t=50sec
t=75sec
t=100 sec
t=150 sec
t=200 sec
t=300 sec
t=400 sec
t=600 sec
t=750 sec
Initial VES, Meas
Initial VES, Calc

Legend (lower):
t=10 sec
t=20 sec
t=40 sec
t=40 sec

Acceleration, g

Soil Depth = 5.4 m
Equivalent Depth = 29m

Soil Depth = 11.2 m
Equivalent Depth = 35m

Soil Depth = 14.6 m
Equivalent Depth = 38m

Soil Depth = 18.2 m
Equivalent Depth = 42m

Soil Depth = 25.6 m
Equivalent Depth = 49m

Soil Input, 28 m
Equivalent Depth = 52m

Time, sec

Excess Pore Pressure, kPa

Soil Depth = 5.4m
Equivalent Depth = 29m

Soil Depth = 11.2 m
Equivalent Depth = 35m

Soil Depth = 18.2 m
Equivalent Depth = 42m

Soil Depth = 25.6 m
Equivalent Depth = 49m

Model 5g   50G

Lead surcharge 494 lbs

796

Hacc 12807   Hacc 12815

denser sand layer, RD = 75%

LVDT stub

Vacc 12814   Hacc 12806, PPT 57

Vacc 12826   Hacc 12817, PPT 56

LVDT 874

Vacc 12610   Hacc 13284, PPT 42

Hacc 12801, PPT 39

LVDT 875

loose sand layer, RD = 50%

Hacc 12613, PPT 48

Vacc 12611   Hacc 12824, PPT 35

108
115
69   365
71
80
70   160
12
35

ACC 13 on left, ACC 12816 on right

Model 5g

B-60

Model 5g (Archtest 2b, with weight)

Excess Pore Pressure, kPa

Cyclic Stress Ratio

Legend:
- t=25 sec
- t=37.5 sec
- t=50 sec
- t=100 sec
- t=200 sec
- t=400 sec
- t=600 sec
- t=800 sec
- t=1000 sec
- Initial VES, Meas
- Initial VES, Calc

Note: Model had 495 lb surcharge
491.5 kPa at 50 g, added 25 m equivalent soil

Soil Input, 28 m

Equivalent Input, 53 m

$f = 1.2$ Hz
$a_{max} = 0.4$ g

Legend:
- t=10 sec
- t=20 sec
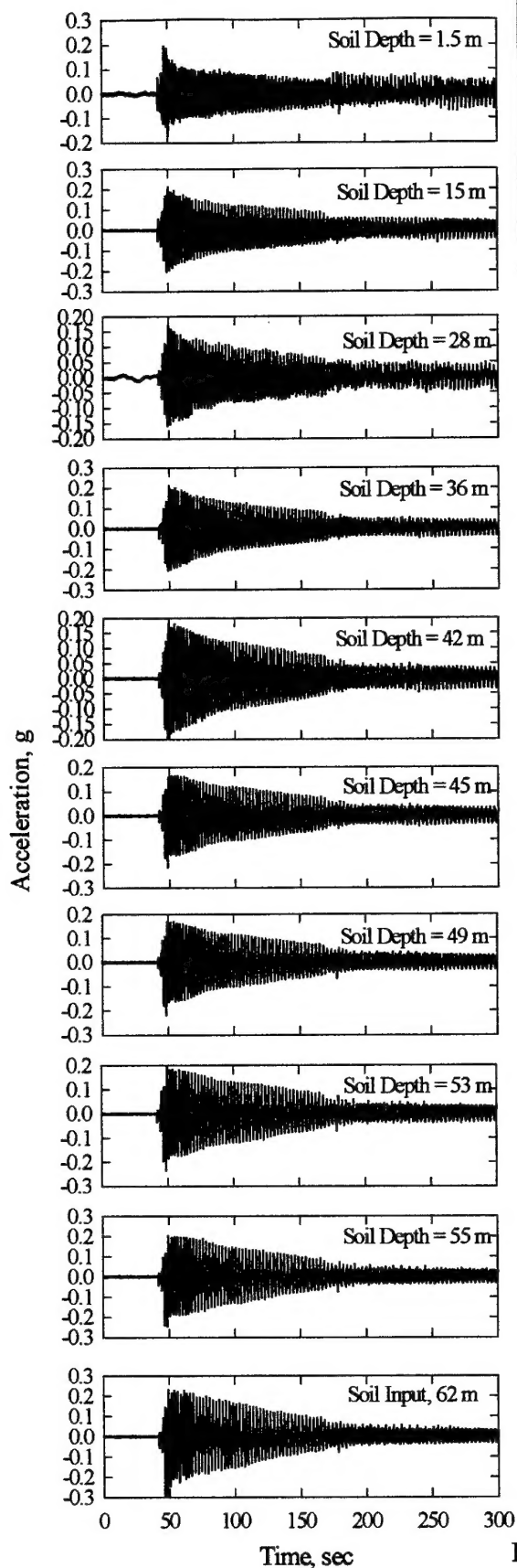- t=40 sec
- t=60 sec
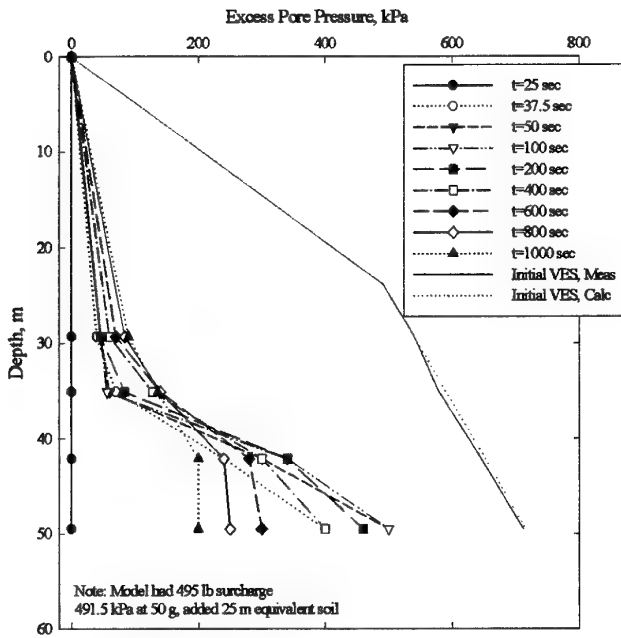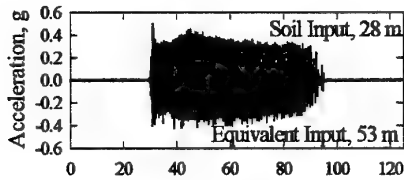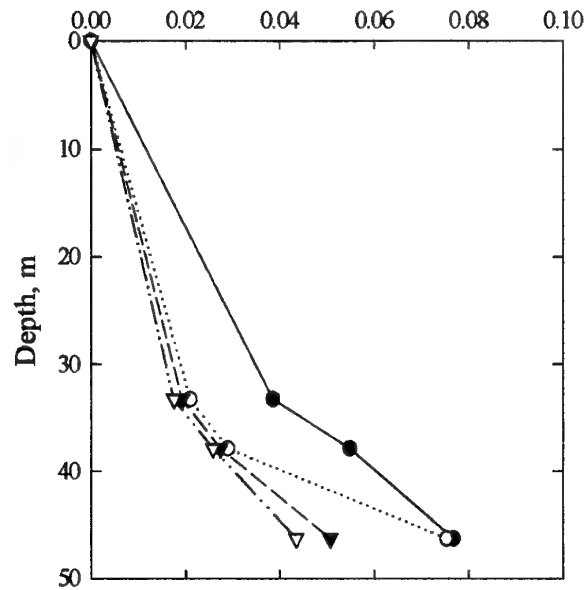
Model 5g-eq1

Cyclic Shear Strain, %
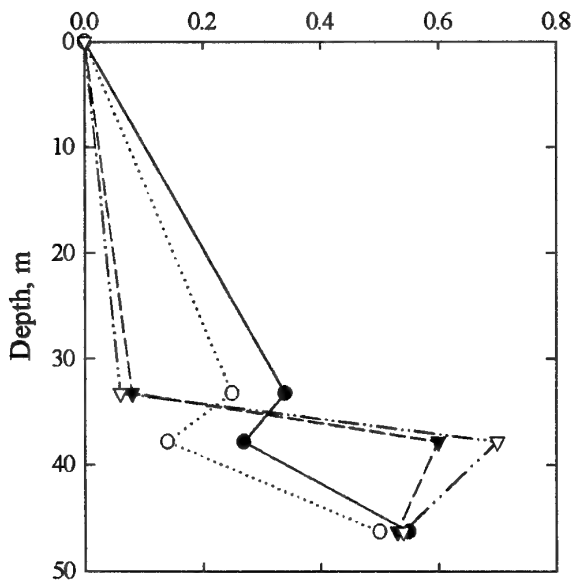
Model 5g-eq1

Cyclic Shear Stress, kPa

Model 5g Stress and strain isochrones

Model 5h

B-62

Model 5h (No Weight 125g)

Cyclic Stress Ratio

f = 0.6 Hz
a_{max} = 0.4 g

Model 5h-eq1

Cyclic Shear Strain, %
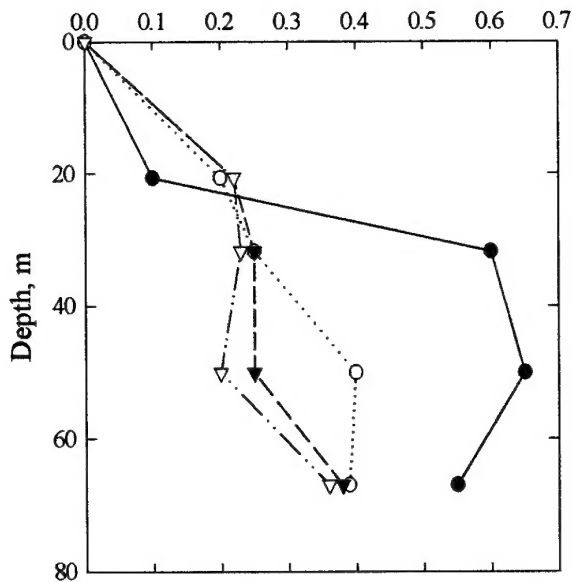
Model 5h-eq1

Cyclic Shear Stress, kPa

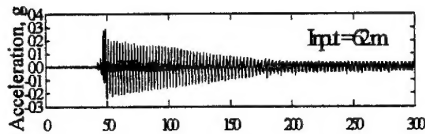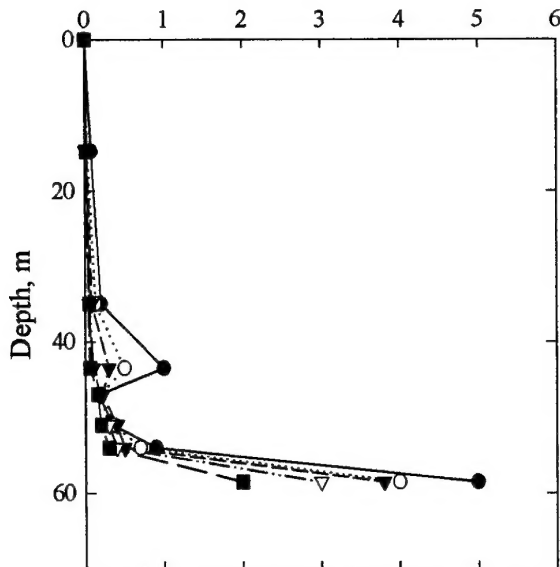**Model 5h Stress and strain isochrones**

Report RSS/J0101R04 Rev 0

Model 5i

B-64

Model 5i (Dry Surcharge 125g)

Excess Pore Pressure, kPa

Cyclic Stress Ratio

Legend:
- t=40sec
- t=50sec
- t=60sec
- t=75sec
- t=90sec
- t=100sec
- t=125sec
- t=200sec
- t=300sec
- t=400sec
- t=800sec
- t=1200sec
- t=1600sec
- Initial VES, Calc

$f = 0.43$ Hz
$a_{max} = 0.22$ g

Input=62m
Acceleration, g

Legend:
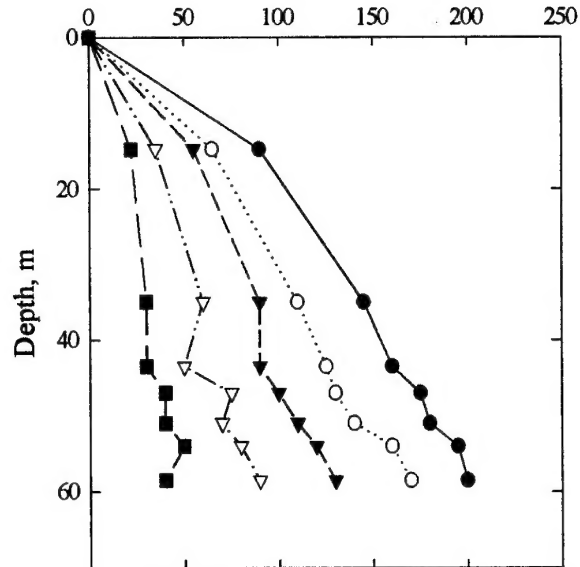- t=25 sec
- t=50 sec
- t=100 sec
- t=150 sec
- t=200 sec
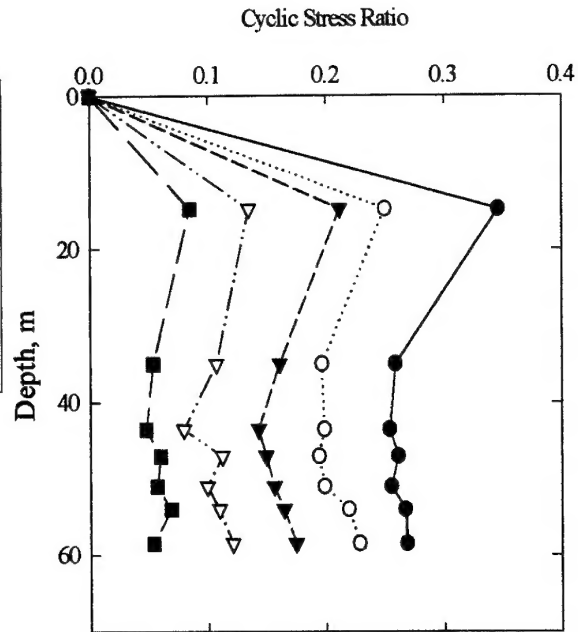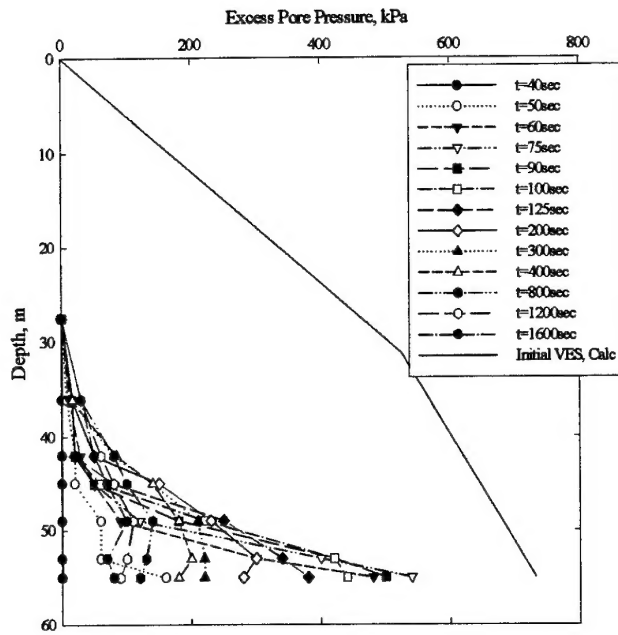
Model 5i-eq1

Cyclic Shear Strain, %

Model 5i-eq1

Cyclic Shear Stress, kPa

Model 5i Stress and strain isochrones

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